The Pennsylvania State University

The Graduate School

Department of Civil and Environmental Engineering

ESTIMATION OF RELATIONSHIPS BETWEEN 85TH PERCENTILE SPEEDS, SPEED DEVIATIONS, ROADWAY AND ROADSIDE GEOMETRY AND TRAFFIC CONTROL IN FREEWAY WORK ZONES

A Thesis in

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by

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ABSTRACT

The *Manual on Uniform Traffic Control Devices* defines a work zone as an area of highway with construction, maintenance or utility work activities. New federal work zone regulations require states to continually pursue improvement of work zone safety and mobility by analyzing work zone crash and operational data to enhance state processes and procedures. Work zone design guidance was identified as an area of needed improvement. Current guidance is heavily based on desirable speed-related outcomes, but knowledge related to actual speed-related outcomes of design and traffic control decisions is limited. The objective of this research was to investigate relationships between speed behavior, roadway and roadside geometrics and traffic control in work zones. The research objective was accomplished through specification, estimation, evaluation and interpretation of a series of econometric models. Four speed-related performance measures were modeled: 85th percentile passenger car speed, 85th percentile truck speed, passenger car speed deviation and truck speed deviation. Data for model estimation were collected in Pennsylvania and Texas work zones. Three issues were addressed by the work zone speed models: contemporaneous correlation between equation disturbances, contemporaneous relationships between dependent variables and autocorrelation. A simultaneous equation model estimated with three-stage least squares was recommended. Effects of work design and traffic control features on speed were observed but small in magnitude. Additional data collection and modeling activities are recommended before direct implementation of speed findings into work zone design practice, including observation of larger samples with greater variability in geometric design elements and investigation of purely predictive modeling techniques. Selected results and conclusions have near-term value. No geometric or traffic control elements showed a direct effect on 85th percentile passenger car speeds. Passenger car speeds were controlled mostly by truck speeds, which were directly influenced by posted speed, work zone type, type of infrastructure and vertical alignment. Truck speed deviations were lower in work zones with a posted speed reduction of 10 or 15 mph than in work zones with no posted speed reduction. In addition, passenger car speed deviations were higher in work zones with a 70 mph posted speed limit compared to other posted speeds. Both of these findings contradict work zone posted speed guidance in the *MUTCD*, that a decrease in posted speed causes an increase in speed variance and that posted speed reductions should be avoided or limited to 10 mph for this reason. In addition, passenger car speed deviations were lower in work zone areas with either a temporary concrete barrier or permanent roadside conditions compared to areas with drums, vertical panels or other similar roadside devices.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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“An expert is a man who has made all the mistakes which can be made in a very narrow field.”

- Niels Bohr

Chapter 1
Introduction

The objective of this research is to investigate relationships between speed behavior, roadway and roadside geometrics and traffic control in work zones. The *Manual on Uniform Traffic Control Devices* (*MUTCD*) defines a work zone as an area of highway with construction, maintenance or utility work activities [**1**]. In addition to providing for the movement of traffic, work zones accommodate mechanized and labor-intensive construction, rehabilitation and maintenance activities. These activities and normal transportation functions (i.e. safety, efficiency and access) are often at cross-purposes. Reduced cross sections, increased curvature and other temporary design and traffic control features may be present, resulting in deviations from pre- or post work zone operations. Effects may be observed on both local and system-wide scales.

Work zones are present during highway improvement projects including new route construction, relocation, reconstruction and restoration, rehabilitation and resurfacing (3R). Work zone environments currently are and will continue to remain prevalent to motorists as illustrated by the following statistics:

- Approximately 12 billion vehicle-miles of travel were exposed to active work zones during 2001; approximately 61 billion vehicle-miles were exposed to inactive work zones [**2**].
- Between 1985 and 2005, vehicle-miles traveled (VMT) increased by approximately 70 percent [**3**], [**4**].
- An estimated 7,141 work zones were present on 163,734 miles of the National Highway System (NHS) during the peak summer roadwork season of 2003. With an average length of 6.1 miles, these work zones occupied an estimated 44,200 miles of the NHS (27 percent of total NHS mileage) [**5**].
- Obligations for Federal-aid highway and highway safety construction programs in the Safe Accountable Flexible Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) increase from $34.4 billion in 2005 to $41.2 billion by 2009 [**6**].

Exposure to work zones will increase as vehicle-miles of travel and funding levels for highway improvement projects increase. Recognition of these trends is reflected in recent evolutions of work zone policies. A brief progression through the history of work zone policy leads to the recognition of an immediate need for this research.

1.1 History of Work Zone Policy

Prior to the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), the results of several studies had indicated a higher level of crash risk in work zones than in permanent highway conditions (e.g., [**7**] and [**8**]). Section 1051 of ISTEA authorized development of a work zone safety program [**9**]:

> "The Secretary shall develop and implement a work zone safety program which will improve work zone safety at highway construction sites by enhancing the quality and effectiveness of traffic control devices, safety appurtenances, traffic control plans, and bidding practices for traffic control devices and services."

The Federal Highway Administration (FHWA) developed and implemented a work zone safety program by publishing a notice in the Federal Register on October 24, 1995 (*60 FR 54562*) [**10**]. This notice officially established the *National Highway Work Zone Safety Program* (*NHWZSP*). The objective of the NHWZSP is to "enhance safety and operational efficiency of highway work zones for highway users – motorists, pedestrians, motorcyclists, bicyclists…and highway workers" [**11**]. The program consists of four components: standardization, compliance, evaluation and innovation. Under each component, future FHWA activities that aid NHWZSP implementation were recommended.

A relevant activity falling under the standardization component was the need to update the FHWA regulation on work zone safety and mobility (*23 CFR 630*, *Subpart J, Traffic Safety in Highway and Street Work Zones* [**12**]). The final updated rule was published in the Federal Register (69 FR 54569) on September 9, 2004 with an effective date of October 12, 2007 [**13**]. A large portion of the old regulation addressed the preparation of a temporary traffic control (TTC) plan that is in agreement with the principles and standards of the *MUTCD* for routing traffic through a work zone. The new regulation discusses comprehensive evaluation and management of broad (e.g. system-wide as well as local) safety and mobility work zone impacts. These impacts will be considered during all phases of project development (as opposed to just construction) and impact-management strategies (e.g. design, technology, contracting) will continue to be developed, improved and evaluated.

The final rule requires States to "implement a policy for the systematic consideration and management of work zone impacts on all Federal-aid highway projects" [**13**]. The policies developed by the States may take the form of processes, procedures and guidance. "States shall continually pursue improvement of work zone safety and mobility by analyzing work zone crash and operational data…to improve State processes and procedures" [**13**]. Work zone design procedures are an area of needed improvement, made evident by a review of current design policy and practice and identified in *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan* [**14**].

1.2 Current Work Zone Design Policy and Practice

At a national level, design guidance for work zones is currently covered by the *MUTCD* [**1**], published by the FHWA, and *A Policy on Geometric Design of Highways and Streets* (*Green Book*) [**15**] and the *Roadside Design Guide* [**16**], both published by the American Association of State Highway and Transportation Officials (AASHTO). A summary of publication scope and their application to work zone design is provided in Table **1-1**. The table illustrates that national guidance related to temporary traffic control devices and crashworthiness of work zone roadside hardware is extensive. Guidance related to work zone geometrics is limited.

Work zone design guidance has been developed in-house by state departments of transportation (DOTs). Of 32 states responding to a recent survey, 25 indicated having a publication related to work zone design [**17**]. The extent of state guidance varied from standard drawings of TTC plans to detailed guidance in areas such as geometric design, drainage, roadside safety and use of traffic barriers and interchange auxiliary lanes [**17**].

Published research documents also include work zone design recommendations [**18**], [**19**], [**20**], [**21**]) (see **2.1**). The most recent were part of a research effort sponsored by the National Cooperative Highway Research Program (NCHRP) to develop design-decision guidance for construction work zones on high-speed highways. Results were published in two media [**17**], [**21**]. An important commonality between national guidance, state DOT-developed guidance and research recommendations is the prominent role of speed in work zone design and traffic control decisions.

Table **1-1**

Table **1-1**: Scope of current work zone design guidance in national publications

Publication	Scope of Publication	Construction Work Zone Design Coverage
MUTCD	Traffic control devices	• Typical applications of temporary traffic control devices for work zones that consider the needs and control for all road users • Limited guidance on work zone geometrics and roadside features
Green Book	Geometric guidance for all types of roads	• Very limited (2 pages) coverage regarding work zone geometrics • No dimensional guidance or quantitative methods are included
Roadside Design Guide	Roadside design practice and principles	• Comprehensive guidance regarding physical characteristics and crashworthiness of work zone traffic control and other roadside devices and barriers • Limited dimensional and quantitative design guidance with respect to clear zones, slopes, horizontal clearance, and temporary barrier use

1.3 The Role of Speed in Work Zone Design

Speed is a primary input into past and current geometric and roadside design processes for permanent facilities. It is an important performance measure used to assess the quality of highway operation. Ideally, the speed that drivers travel on a facility should match the intended purpose of that facility and be harmonious with the surrounding environment. This is not always the case. Most recent research and opinion recognize that driver speed is a “complex issue involving engineering, driving behavior, education and enforcement” [**22**].

Speed is also prominent in current work zone design policies and practice. It is an input to several decisions related to TTC covered by the *MUTCD* (see Table **1-2**). In addition, the *MUTCD* recommends an overall design philosophy of maintaining upstream or pre-work zone speeds if practical and minimizing magnitudes of speed reductions if necessary. The following excerpts illustrate this philosophy [**1**]:

“The basic safety principles governing the design of permanent roadways and roadsides should also govern the design of TTC zones. The goal should be to route road users through such zones using roadway geometrics, roadside features, and TTC devices as nearly as possible comparable to those for normal highway situations.”

“Reduced speed limits should be used only in the specific portion of the TTC zone where conditions or restrictive features are present.”

“A TTC plan should be designed so that vehicles can reasonably safely travel through the TTC zone with a speed limit reduction of no more than 10 mph.”

“A reduction of more than 10 mph in the speed limit should be used only when required by restrictive features in the TTC zone. Where restrictive features justify a speed reduction of more than 10 mph, additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and additional TTC warning devices should be used.”

Limiting speed reductions to 10 mph is based on desirable speed variance effects:

“Smaller reductions in the speed limit of up to 10 mph cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph from the normal speed limit has been shown to be more effective.”

Table **1-2**

Table **1-2**: Summary of speed-related temporary traffic control decisions in the *MUTCD*

Traffic control decision	**Speed measure used as decision input**
Location of first advanced warning sign	Speed limit
Distance between advance warning signs	Speed category of roadway (e.g. low-speed, high-speed)
Stopping sight distance	Posted speed, off-peak 85th percentile speed prior to work or anticipated operating speed
Length of taper	Posted speed, off-peak 85th percentile speed prior to work or anticipated operating speed
Distance between taper devices	Speed limit
Use of temporary traffic barriers	Speed of traffic

The speed-related design philosophy endorsed by the *MUTCD* is consistent with state DOT practice and recommended design procedures in research literature [**17**], [**21**], [**19**].

1.4 Research Objective

The speed-related design philosophy discussed in **1.3** is logical, but difficult to apply given the current state of work zone speed-related knowledge. Several observations support this general conclusion:

- Although current work zone design guidance is heavily based on desirable speed-related outcomes (e.g. maintaining certain operating speeds, minimizing speed variance), knowledge related to actual speed-related outcomes of design decisions is limited (see **2.2**). This includes speed variance effects of posted speed reductions, which is the basis for current work zone design policy and practice.
- Speed-related work zone design decisions use a variety of speed inputs interchangeably (e.g. speed limit, speed category, 85th percentile speed and design speed). Relationships between these measures are not consistent for permanent roadways or work zones.

- Existing and proposed design and traffic control practices are based on achieving desirable speed magnitudes while minimizing speed variance. These objectives may be complimentary or conflicting depending on the design or traffic control decision.
- Recommendations based on research results for posted speed reductions in work zones have been applied to other speed measures (e.g. design speed, target speed, anticipated operating speed). These measures may or may not be surrogates for actual operating speeds.
- Inconsistencies between pre-work zone operating speeds, desired operating speeds, posted speed and actual operating speeds lead to reactive implementation and unanticipated expenditures for work zone speed management strategies (e.g. police presence, intelligent transportation systems) when actual speeds are higher than intended speeds or after the occurrence of one or more severe crashes.

The objective of this research is to investigate relationships between speed behavior, roadway geometrics and traffic control in work zones. Current and recommended work zone design processes would benefit from an understanding of the speed-related outcomes of design and traffic control decisions. The research need is illustrated by the bulleted observations above and is consistent with specific requirements in the final rule on Work Zone Safety and Mobility (i.e. analyzing “operational data…to improve State processes and procedures” [**13**]). The location of this research in an overall scheme to improve work zone design practice is proposed in Figure **1-1**.

The research objective is accomplished through specification and estimation of a series of econometric models. The models explain variation in speed-related performance measures based on work zone design and traffic control features as well as other speed-related measures (see **3.7**). Current work zone design guidance is based on desirable outcomes related to speed magnitude and speed variance. Eighty-fifth (85th) percentile free-flow speed is the most commonly referenced measure of operating speed used in design and traffic control decision processes. Standard deviation of speed (referred to as *speed deviation* in the remainder of the document) is directly related to speed variance and has the same measurement units as operating speed (e.g. mph). Passenger cars and trucks (see **3.1.2** for definitions) have inherently different physical dimensions and performance capabilities. Work zones often introduce restrictive geometry including reduced sight distance, narrower cross sections and increased curvature. Different speed behavior of passenger cars and trucks is expected.

Given the preceding discussion, four speed-related performance measures are modeled in this research:

- 85th percentile passenger car speed;
- 85th percentile truck speed;
- Passenger car speed deviation; and
- Truck speed deviation.

No other work zone speed models of this type exist. These first modeling steps are intended to discover possible associations between work zone variables and vehicle speeds. In the absence of other information, they may also be used for forecasting or policy development. Results and conclusions will be presented in a way amendable to all three applications.

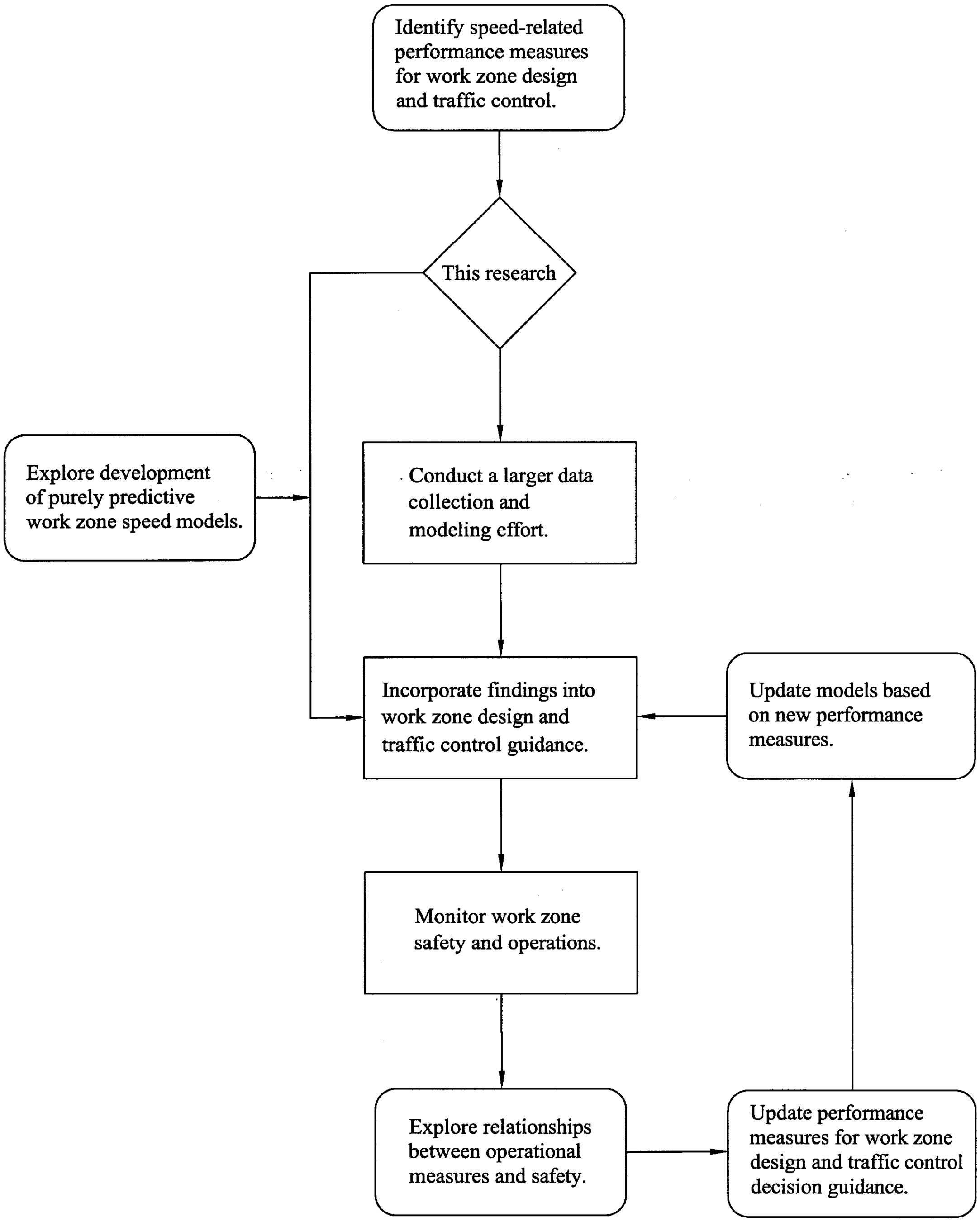

Figure **1-1**: Location of research in proposed process to improve speed-related work zone design guidance

1.5 Organization of Thesis

The thesis consists of seven chapters:

- A general introduction is provided in Chapter **1**. The need for this research is demonstrated through a review of past and current work zone policy and design practice. The chapter concludes with a specific research objective and the place of this research in an overall process to improve work zone design guidance.
- Published work related to the research objective is summarized in Chapter **2**. Specifically, the focus is on findings related to the role of speed in work zone design and effects of work zone design and traffic control features on operating speeds. Techniques used to model relationships between speed and roadway features on permanent roadways are also identified.
- The research scope, data collection and general modeling philosophy is defined in Chapter **3**. Data collection scope and methods, definitions and descriptive statistics of variables, characterization of data, identification of modeling techniques and general modeling philosophy are addressed.
- Model specifications and estimations with only exogenous explanatory variables (e.g. work zone geometry and traffic control) are addressed in Chapter **4**. Estimator details, relevant hypothesis testing and estimation results are provided for ordinary least squares regression, seemingly unrelated regression and first-order autoregressive models. The chapter concludes with a summary of statistical findings.
- Specifications and estimation results for simultaneous equation models are summarized in Chapter **5**. Estimator details, relevant hypothesis testing and estimation results are provided for two-stage least squares, three-stage least squares and ordinary least squares regression. Simultaneous equation models that account for autocorrelation are also included. The chapter concludes with a summary of statistical findings.
- An evaluation of alternative model structures and model recommendations are included in Chapter **6**. Detailed interpretations of model parameters are also provided.

- A summary of the research effort, conclusions of this research and recommendations for future work are addressed in Chapter **7**.

Chapter 2
Literature Review

This chapter summarizes published work related to the research objectives identified in Chapter **1**. A large body of speed-related work zone literature exists. A significant portion of this literature consists of site-specific before-after evaluations of speed dampening strategies and devices including police presence, flagging procedures, temporary rumble strips and different speed displays. These types of studies are not particularly relevant to this work and were not included in the literature review. The review focused on the more limited collection of published findings that addressed:

- The role of speed in work zone design philosophy; and
- Operating speed effects of work zone design and traffic control features.

In addition, techniques used to model relationships between speed and roadway features on permanent roadways were identified.

2.1 The Role of Speed in Work Zone Design Philosophy

Speed-related work zone design issues are prevalent. Without the benefit of much completed or ongoing work zone research at the time, authors of *NCHRP Synthesis of Highway Practice 1* concluded:

> "Optimum speeds through work zones need to be determined by further study and research. Current practice suggests that there is a wide range of opinions as to whether or not traffic should be slowed down…or whether continuation at normal highway speeds produces the best performance through work zones." [**23**]

Graham et. al. verified the existence of the two work zone speed philosophies through discussions with highway agency personnel from 25 states [**18**]. A work zone design speed equal to the design speed of the highway upstream of the work zone was recommended if maintaining normal speeds was the objective. A work zone design speed lower than the upstream design speed as well as an effective method of speed dampening was acceptable if a speed reduction through the work zone was desired. Alternative speed dampening strategies were identified: advisory and regulatory speed limits, signal control, flagging, traffic pacing and physical restrictions (e.g., reduced lane widths).

In the same study, before-during crash data and work zone characteristics were collected for 79 projects in seven states: Colorado, Georgia, Michigan, Minnesota, New York, Ohio and Washington. The following results related to work zone speed practices were reported:

- The increase in number of accidents per month in all work zones (compared to respective before periods) was greater in work zones with a speed reduction (by advisory or regulatory signing) than those without.
- Work zones in urban areas with no speed reductions experienced a 14 percent increase in accidents when compared to the before period; urban work zones with speed reductions experienced a 6 percent increase.
- Work zones in rural areas with no speed reduction experienced a 2.6 percent increase in accidents when compared to the before period; rural work zones with speed reductions experienced a 16.4 percent increase.
- Speed reduction was positively correlated with overturning accident rate.

Richards et. al. merged the two aforementioned work zone speed philosophies into a basic approach of work zone speed control [**24**]:

> "Every effort should be made to design work zones to safely accommodate traffic at normal speeds. When it is impossible or impractical to accomplish this goal, safe, effective and economical means should be used to reduce speeds to the appropriate level."

Applying this philosophy, Richards and Dudek developed recommendations for implementing speed control at construction and maintenance work zones [**19**]. Implementation involved four steps: 1) determine the need for speed reduction; 2) select a reasonable speed; 3) select a speed control treatment; and 4) select the location for treatment implementation. Recommended considerations under each of these steps are summarized in Figure **2-1**.

Figure **2-1**

Step 1: Determine the need for speed reduction. Attempts to reduce speed should be based on an identifiable need, not on intuition or general policy. Speed reduction should be aimed at reducing and/or preventing the number and/or severity of work zone accidents. Potential speed related hazards include hidden or unapparent work zone features (e.g. changes in alignment, edge drop-offs), reduced design speed, or a work space that is not shielded by a barrier or other device.

Step 2: Selection of a reasonable speed. Reasonable speed was defined as "the fastest speed that can still be considered safe." Depending on the facility type, drivers will only reduce speeds to a certain level regardless of the presence of speed-dampening treatments. Similarly, work zone design speeds should not be lower than what drivers would reasonable expect or tolerate on a given facility type. Drivers will lose respect for traffic control and treatments encouraging unreasonably low speeds.

Step 3: Selection of speed control treatment. Speed dampening treatments were classified as *passive* or *active* speed control. Passive speed control refers to posting a reduced speed (regulatory or advisory) on a static sign. Passive control alone is generally sufficient at sites where the hazards are obvious and drivers have enough time and information to make a reasonable speed selection. Active control refers to techniques that restrict movement, display real-time information, or enforce compliance to a passive control. Active control is needed in situations where drivers are unable or unwilling to select appropriate speeds. In selecting a speed dampening treatment, considerations should be given to the duration of the hazard, facility type, desired speed reduction, implementation cost, and institutional constraints (e.g. availability of selected treatment).

Step 4: Selecting a location for treatment implementation. The speed dampening treatment should first be initiated 500 to 1000 feet upstream of the speed related hazard within the work zone. This allows drivers time to react while keeping the speed message fresh in their minds when hazard is reached. Lane width reductions should be initiated 500 to 1000 feet upstream of the speed related hazard and continued to a point just downstream of the hazard. Speed dampening treatments should be placed in areas where drivers will not be overloaded with too much information. Treatments may lose their impact as drivers travel further downstream; if other speed-related hazards exits, additional treatments may be needed.

Figure **2-1**: Recommendations for implementing speed control at construction and maintenance work zones [**19**]

Migletz et. al. completed a study aimed at developing a uniform procedure for determining work zone speed limits. Results and recommendations were published in two documents ([**20**], [**25**]) and are one basis for current work zone posted speed guidance in the *MUTCD* [**1**].

At the time of the study, returned surveys from 45 state highway agencies revealed three general policies for establishing work zone speed limits: 1) avoid the need for speed limit reductions whenever possible; 2) provide a blanket speed limit reduction at all work zone sites; 3) determine the need for a work zone speed limit reduction based on specific factors. States using each of the policies were represented in an operational and safety data collection effort in 68 work zones across seven states. The work zones were categorized by area type (urban, rural), highway type (freeway, multilane, two-lane) and location of work (traveled way, detour, shoulder, roadside). The sites had speed limit reductions ranging from 0 to 30 mph. Speed studies were conducted at 27 of the 68 sites (22 of the 27 were classified as “basic study sites”). At each site, operating speeds were collected at one upstream location and one location inside the work zone. Accident data were obtained for 66 of the 68 work zones.

Analyses addressed changes in mean and 85th percentile speeds, speed limit compliance and change in speed variance. Results related to mean and 85th percentile speeds are summarized in Table **2-1**. The mean speed of traffic in the work zone was less than the mean speed upstream of the work zone by a statistically significant amount for 19 of the 22 basic study sites. At sites where the speed limit was not reduced, the mean speed of cars and trucks decreased by 4.8 and 5.5 mph, respectively. In general, reductions in mean speed increased as speed limit reduction increased. However, reductions in mean speed were consistently less than the magnitude of speed limit reduction. Results for 85th percentile speeds were similar to those for mean speeds.

Table **2-1**

Table **2-1**: Summary of reductions in mean and 85th percentile speeds between upstream and work zone locations [**20**]

Speed limit reduction	Number of sites	Reduction in mean speed (mph) between upstream and work zone location			Reduction in 85th percentile speed (mph) between upstream and work zone location		
		All vehicles	Cars	Trucks	All vehicles	Cars	Trucks
0	5	5.1	4.8	5.5	4.5	3.7	4.9
10	4	7.2	7.7	5.5	5.5	6.5	6.4
15	3	7.8	8.2	4.5	7.0	7.8	1.7
20	7	13.6	13.9	12.4	11.8	9.2	10.8
25	2	12.7	12.7	12.6	10.0	9.0	11.8
30	1	20.7	24.6	17.8	18.0	21.0	21.0

Speed variance in the work zone was higher than upstream speed variance at most of the sites. The difference was reported as significant at approximately half of the sites. In most of the remaining cases, speed variance in the work zone was higher than upstream speed variance, but the differences were described as "not large enough to be statistically significant" [**20**]. The work zone speed variance was lower than upstream variance in the remaining few cases. Details of statistical tests were not provided. The results in Table **2-2** show that the smallest increase in speed variance occurred for speed limit reductions of 10 mph. However, because of the small sample sizes and high site-to-site variability, the differences across levels of speed limit reduction were not statistically significant.

Table **2-2**

Table **2-2**: Summary of speed variance results [**20**]

Speed limit reduction	Number of sites	Percent increase in speed variance (mph) between upstream and work zone location		
		All vehicles	Cars	Trucks
0	5	61.2	81.8	11.8
10	4	34.1	46.8	14.4
15	3	86.7	79.6	159.3
20	7	82.6	93.5	182.9
25	2	92.6	206.3	32.5
30	1	80.6	70.8	94.6

The speed study was supplemented with an accident study to determine which work zone speed limit reduction resulted in the lowest accident rates. The analysis was conducted for separate groups defined by area type, highway type, and location of work activity. The largest group consisted of 27 sites involving traveled way (i.e. lane closure) or detour (i.e. median crossover) work zones on rural freeways. The results for this group are summarized in Table **2-3** and appear consistent with the results of the speed variance analysis. The minimum percent increase in accident rate from before to during periods occurred for a 10 mph speed limit reduction. The mean differences in total accident rates across speed limit reductions were reported as not statistically significant. The differences in fatal and injury accident rates were statistically significant. Details of statistical tests were not provided. The results for the remainder of the analysis groups were inconsistent and inconclusive due to very small sample sizes.

Table **2-3**

Table **2-3**: Percent increase in accident rate by speed limit reduction for traveled way and detour work zones on rural freeways [**20**]

Speed limit reduction	Number of sites	Mean % increase in:	
		Total accident rate	Fatal and injury accident rate
0	5	59.5	98.6
10	9	42.3	4.1
15	4	54.4	147.9
20	6	99.8	112.5
25/30	3	(a)	(a)
(a) insufficient data			

Based on the speed and accident study results, a review of current practice and a survey of motorists, contactors and insurance carriers, the researchers concluded that:

- Work zone speed limit reductions should be avoided wherever possible; particularly in work zones where all work activities are located on the shoulder or in roadside areas or when no work activities are underway.
- A 10-mph speed reduction below the normal speed limit is desirable when:

  - Work takes place on or near the traveled way, particularly on rural freeways; and
  - Personnel are required to work extended periods in an unprotected position within 10 feet of the edge of the traveled way.
- Work zone speed limit reductions larger than 10 mph are undesirable and should be avoided except where required by restricted geometrics or other work zone features that cannot be modified.

Mahoney et. al. developed guidance related to work zone speed management and work zone design speed [**21**]. The guidance was based on the principle that “Speed-related decisions within specific domains (i.e. design, regulatory and speed management) should be consistent with an overall strategy” [**21**]. An example process for work zone speed-related decisions is illustrated in Figure **2-2**.

The target speed was defined as the desirable 85th percentile free-flow speed within a construction work zone. Target speeds that meet or nearly meet driver expectations based on previous experience were considered desirable (i.e. same or only slightly lower than pre-work zone speeds). If a target speed comparable to approach speeds is not possible due to the presence of a restricting feature, then a new target speed is selected based on the restrictive feature. If the restrictive feature requires a speed reduction of more than 10 mph, then “driver notification should be provided through consistent, credible and complimentary information sources” [**21**]. A work zone design speed equal to or slightly greater than the final target speed is recommended.

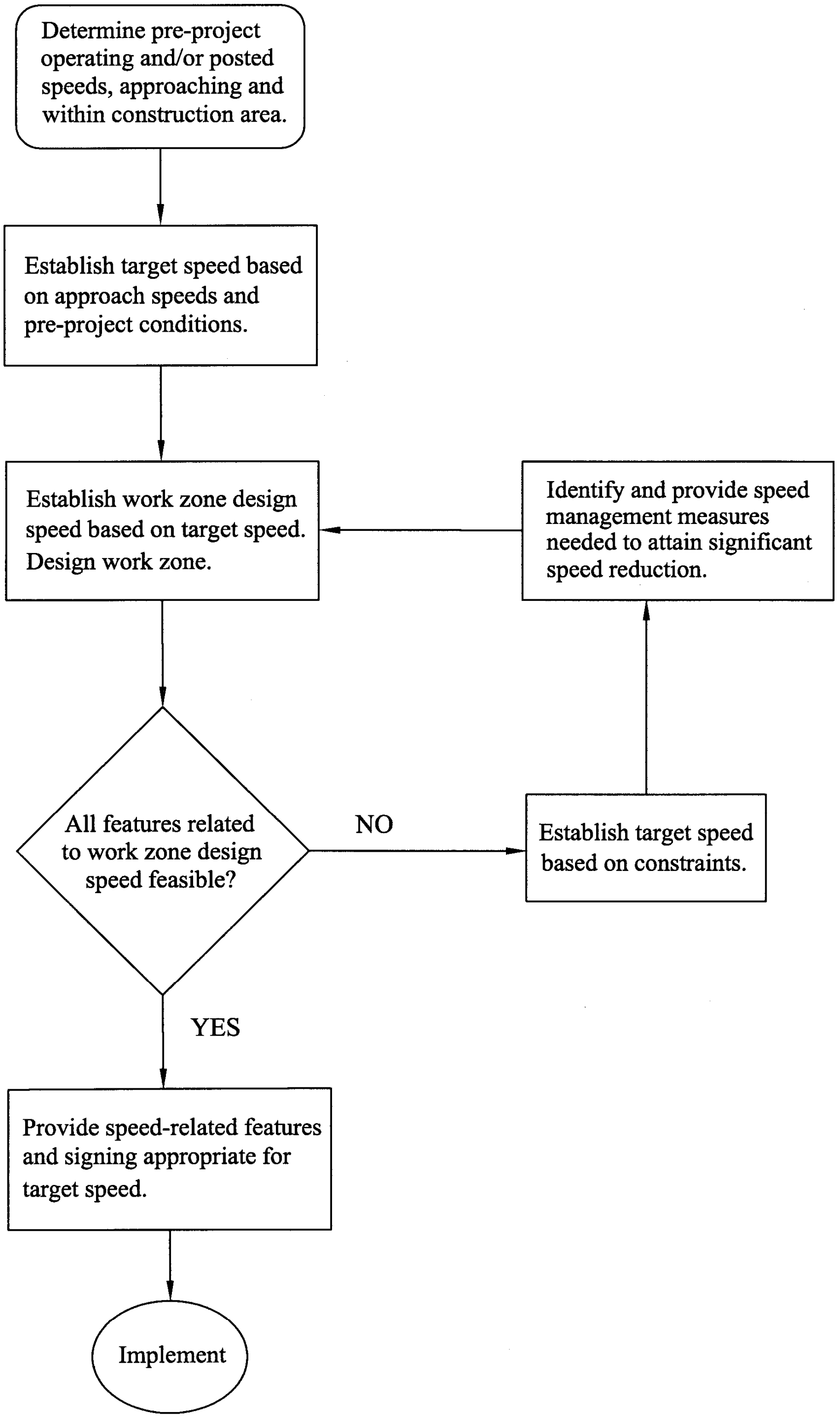

Figure **2-2**: Work zone speed-related decision process [**21**]

The speed-related work zone design processes proposed in [**19**] and [**21**] are consistent with current national guidance: maintain or nearly maintain approach speeds if practical. Mahoney et. al. reference the 10-mph posted speed reduction guidance in the *MUTCD*, which was based on the speed variance results in Table **2-2**, in their discussion of target speed selection. Conceptually, existing and recommended speed-related design practices are logical, but incomplete. Two observations support this general conclusion:

- Existing and proposed design and traffic control practices are based on achieving desirable speed magnitudes while minimizing speed variance, objectives that may be conflicting or complimentary depending on the design or traffic control decision.
- Recommendations based on research results for posted speed have been applied to other speed measures (e.g. design speed, target speed); these measures may or may not be surrogates for actual operating speeds.

These observations are a direct result of limited knowledge related to operating speed outcomes of work zone design and traffic control decisions. Existing and recommended work zone design processes would benefit from such knowledge. A literature review demonstrated that a limited amount of information regarding speed magnitude and variance effects of work zone design and traffic control decisions exists.

2.2 Operating Speed Effects of Work Zone Design and Traffic Control Features

This section summarizes published findings related to speed magnitude and variance effects of general design decisions and features common to most work zones. This includes typical signing and channelizing applications, work zone configuration and other geometric features and dimensions (e.g. length, alignment, cross section). The number of relevant studies identified and their respective results were limited. Work zone features and speed measures addressed by each identified study are listed in Table **2-4** followed by a summary of results organized by work zone feature. The findings reference two types of work zone configurations: lane closures and median crossovers. For definitions, see **3.1.1**.

Table **2-4**

Table **2-4**: Summary of speed-related work zone literature

Study	**Work zone features**	**Speed measures**
Graham et. al. [**18**], [**26**]	Regulatory and advisory speed signing Work zone location	Mean speed (all vehicles)
Graham and Migletz [**27**]	Work zone type Channelizing devices Work zone location Crossover design Length of TLTW section	Mean speed (all vehicles) Mean car speed Mean truck speed Coefficient of speed variation (all vehicles)
Rouphail and Tiwari [**28**]	Work activity	Space-mean speed Speed reduction
McCoy and Peterson [**29**]	Length of TLTW section	Standard deviation of speed Speed range 10 mph pace speed Skewness of speed distribution
Jiang [**30**]	Work zone type	Mean speed
Benekohal and Wang [**31**], [**32**], [**33**]	Work zone location	Mean car speed Mean truck speed
Migletz et. al. [**20**], [**25**]	Regulatory speed signing	Change in mean speed (all vehicles) Change in car mean speed Change in truck mean speed Change in 85th percentile speed (all vehicles) Change in 85th percentile car speed Change in 85th percentile truck speed Change in speed variance (all vehicles) Change in car speed variance Change in truck speed variance
Benekohal et. al. [**34**]	Work activity	Speed reduction
Zhu and Saccomanno [**35**]	Work zone type	Speed variance
Chitturi and Benekohal [**36**]	Lane width	Mean speed (all vehicles) Mean car speed Mean truck speed Speed variance (all vehicles) Car speed variance Truck speed variance

2.2.1 Advisory and Regulatory Speed Signing

Two studies reported speed effects of advisory and regulatory speed signing. Graham et. al. collected operating speed data at three work zone sites to test the effects of different speed reduction methods and concluded that [**18**], [**26**]:

- Reduced regulatory or advisory speed postings do not reduce mean vehicle speed.
- Drivers adjust speed and position based on the environment (i.e. work zone geometrics, lateral clearance and other devices) more than on signage.

A more recent study by Migletz et. al. examined relationships between change in posted speed from work zone approaches to work zones and the corresponding change in mean speed, 85th percentile speed and speed variance [**20**], [**25**]. A detailed review of the methodology and findings is provided in **2.1**.

2.2.2 Channelizing Devices

Graham and Migletz conducted operational studies at 22 construction sites with median crossovers and two-lane, two-way (TLTW) operations [**27**]. The centerline treatments of the TLTW sections were portable concrete barrier, tubular markers, asphalt curb with tubular markers, raised pavement markers, and striping (double solid yellow lines). The following speed-related results were reported without the support of statistical testing:

- TLTW sections separated with raised pavement markings had the highest mean car and truck speeds in the direction with the median crossover; mean speeds for the remaining centerline treatments were very close in the crossover direction.
- In the direction without the median crossover, TLTW sections with raised pavement markings had the highest mean car and truck speeds; truck speeds with striping were nearly as high as truck speeds with raised pavement markings; car speeds with striping were 3 mph slower than car speeds with raised pavement markings.
- In the direction without the median crossover, TLTW sections with either raised pavement markings or striping have speeds substantially higher than other treatments for work zones with TLTW roadways less than two miles long.

- Speed reductions from the work zone approach to the TLTW sections were approximately equal for tubular markers, asphalt curb with tubular markers, and portable concrete barriers.
- The mean coefficient of speed variation (standard deviation ÷ mean) was lowest in the TLTW sections with raised pavement markings.
- Centerline treatments associated with lower speeds in the TLTW section were also associated with a higher coefficient of speed variation.

2.2.3 Location in Work Zone

Based on data from only one median crossover work zone collected by Graham et. al., the slowest speeds occurred at the beginning of the crossover followed by the end of the lane taper [**18**]. In a much larger study, analysis of speed data collected at different locations in 22 median crossovers with TLTW operations resulted in the following findings applicable to both directions of travel [**27**]:

- On average, vehicle speeds were 10 mph slower in the TLTW section than on the work zone approach.
- For both cars and trucks, the mean speed in the TLTW section was higher in the direction without the median crossover.
- CVs in the TLTW sections were higher in the travel direction with the median crossover.
- Truck mean speeds were an average of 1 to 3 mph slower than car mean speeds at all observed locations.

In the direction with the median crossover [**27**]:

- Speeds decreased substantially from the work zone approach to the first crossover, then increased in the TLTW section, but not to speeds as high as those on the approach.
- Mean speeds decreased from the start to the middle of the first crossover and also decreased from the middle to the end.
- Vehicles slowed substantially from the middle of the TLTW section to the start of the second crossover, but not as much as from the approach to the start of the first

crossover. This result was attributed to greater speeds on the approach than in the middle of the TLTW section.

- Mean speeds at the beginning and middle of the second crossover were nearly equal for both cars and trucks.

Data collected in the same study at 14 lane closure work zones showed that approach speeds were approximately 7.5 mph higher than speeds in the work area [**27**]. Mean truck speeds were approximately 1 to 2 mph slower than car mean speeds at this location [**27**].

Benekohal et. al. compared passenger car and truck behavior at different locations in a single lane closure work zone [**31**], [**32**], [**33**]. The following were relevant speed-related conclusions:

- Passenger vehicle speed distribution was bi-modal at the start of the lane taper.
- Mean passenger car speeds were lowest and car speed variance highest in the work area.
- Almost all passenger vehicles traveled faster than the work zone posted speed at all locations except the work area, where 70 percent traveled faster than the work zone posted speed.
- Mean speed and speed variance for trucks were lower than for passenger cars at all locations.
- Mean truck speed was lowest in the work area.
- Speed variance for trucks was lowest in the work area and at the beginning of the lane taper.
- More than 90 percent of trucks traveled faster than the work zone posted speed at all locations except the work area, where more than 50 percent traveled faster.
- The mean speed profile of trucks was parallel to that of cars but approximately 4 to 7 mph slower.

2.2.4 Work Zone Type

Two studies compared speeds in lane closures to speeds in median crossover work zones. A third simulated differences between left and right lane closures. Graham et. al. reported that mean speeds in the work area of 14 lane closure work zones were approximately equal to mean speeds in the TLTW section of 22 median crossover work zones in the direction without the crossover [**27**].

Jiang analyzed traffic flow in lane closure and median crossover work zones on four-lane divided freeways in Indiana [**30**]. Four work zone classifications were used to disaggregate the analysis: right lane closure, left lane closure, crossover (crossover direction) and crossover (opposite direction). Sample sizes within each classification were 3, 2, 3, and 4 work zones, respectively. Mean speeds across work zone types were approximately equal during uncongested conditions. Mean speeds in lane closures were higher than in median crossovers during congested flow.

Zhu and Saccomanno investigated operational effects of left and right single lane closures on six-lane freeway segments [**35**]. Work zone scenarios were modeled in INTEGRATION, a microscopic simulation model capable of modeling lane drops and lane additions from the left or right side and estimating volume, speed and occupancy at specified locations of freeway segments [**37**]. The modeled work zones included five areas defined in the *MUTCD*: advance warning, transition, buffer, work and termination. Speed variance was higher for the left lane closure in all work zone areas and for all flows. There were no discernable differences in mean speeds between left and right lane closures.

2.2.5 Length of Two-Lane, Two-Way Sections in Median Crossover Work Zones

McCoy and Peterson investigated relationships between the length of TLTW segments and four measures of speed distribution: standard deviation (mph), range (mph), percentage in the 10-mph pace and skewness [**29**]. Speed data were collected on four TLTW segments ranging from 6.68 to 7.22 miles. At least 100 free-flow speeds were measured at the one-third and two-thirds point of the TLTW segment in the direction with the median crossover and the one-third, two-thirds and end point in the direction without the crossover. Four separate regressions were estimated to investigate the relationships between each of the speed distribution measures and the distance from the beginning of the TLTW segment (measured in miles). No statistically significant relationships were found.

Graham et. al. reported that work zones with TLTW roadways longer than 2 miles had higher mean speeds than those less than two miles long [**27**].

2.2.6 Median Crossover Design

Graham et. al. compared speed characteristics on median crossovers with flat diagonal versus reverse curve designs [**27**]. The flat diagonal crossovers did not have any horizontal curvature or superelevation beyond normal cross slope. The reverse curve designs had two horizontal curves within the crossover that may or may not have had superelevation beyond normal crown. Speed data were collected at eight work zones, four with flat diagonal designs and a right approach lane closure, one with a flat diagonal design and a left approach lane closure, two with reverse curve designs and a right approach lane closure and one with a reverse curve design and a left approach lane closure. The following speed-related results were reported:

- Speeds were lowest at the middle of the first crossover and increased at the end of the crossover for the four sites with flat diagonal designs and a right approach lane closure.
- Speeds were highest in the middle of the first crossover and lowest at the beginning and end of the crossover for the one site with a reverse curve design and left approach lane closure.
- Vehicles decelerated at the start of the first crossover at all sites; subsequently, vehicles were more likely to accelerate at the middle and end of flat diagonal crossovers than at those locations on reverse curve designs.
- Speeds in the middle of the crossover are lower than speeds at the beginning of the crossover for flat diagonal exiting crossover designs; the opposite is true for reverse curve designs.

2.2.7 Lane Width

Chitturi and Benekohal studied the free-flow speed reduction effects of reduced lane widths with no right or left lateral clearance using data from four lane closure work zones on four-lane Interstate highways in Illinois [**36**]. All four sites were long-term construction work zones with work zone posted speeds of 55 mph and up- and downstream posted speeds of 65mph. The characteristics of both the sites and free-flow speeds are summarized in Table **2-5**.

Table **2-5**

Table **2-5**: Site characteristics and free-flow speeds at four Illinois construction work zones [**36**]

Site	1	2	3	4
Lane width (ft)	16	12	11	10.5
Lateral clearance left (ft)	0	0	0	0
Lateral clearance right (ft)	0	0	0	0
Volume (vph)	845	524	1294	750
# of free-flowing cars	265	237	135	111
# of free-flowing heavy vehicles	143	238	12	47
Avg. FFS of all vehicles (mph)	57.9	54.4	50.0	47.2
Avg. FFS of cars (mph)	58.5	54.6	50.2	47.9
FFS of heavy vehicles (mph)	56.9	54.2	46.7	45.7
Variance of FFS for all vehicles (mph^2)	25.67	23.82	37.74	26.54
Variance of FFS for cars (mph^2)	27.89	28.74	36.98	30.49
Variance of FFS for heavy vehicles (mph^2)	21.12	18.94	38.06	14.25

Differences between average free-flow speeds for all vehicles were statistically significant for all pairwise lane width comparisons. Average free-flow speeds of passenger cars were greater than for trucks. The differences were statistically significant at all but one site (Site 2). The following speed-related conclusions were reached [**36**]:

- Using a base lane width of 12 feet, proposed free-flow speed reductions for lane widths of 11.5, 11, 10.5 and 10 feet were 2.1, 4.4, 7 and 10 mph, respectively.
- Narrow lane widths affected free flow speeds of heavy vehicles more adversely than passenger cars; this should be accounted for in calculations of work zone passenger car equivalents.
- Free-flow speed reduction due to no shoulder on either side of the traveled way was 5.6 mph; these data were available in only work zone with a 12 foot lane width and an assumed base free-flow speed (5 mph higher than the work zone posted speed).

2.2.8 Work Activity

Two studies attempted to quantify speed effects of work intensity and proximity. Rouphail and Tiwari conducted field studies to examine the range of speed-flow relationships in work zones and isolate the effects of work zone activity [**28**]. Over 21,000 vehicle observations were collected at four construction projects on four-lane Interstate and Interstate-look-alike facilities. The projects were all located within 60 miles of Chicago; all locations but one were considered rural. Work zone configurations were all single lane closures without median crossovers.

Speed reductions due to work activity were determined by comparing observed to predicted mean speeds for 103-five minute observations across the four work zone sites. On average, observed mean speeds were 3 mph less than predicted speeds after controlling for lane width, volume, and truck occurrence. These differences were attributed to factors not controlled for, including work activity.

An activity index (AI) was calculated as the sum of numerical codes for:

- Proximity of work activity to travel lane;
- Active crew size in the work area;
- Relative size of equipment;
- Presence of flaggers;
- Noise level; and
- Dust level.

Mean speed reduction for five-minute intervals with a high AI (> 8) was approximately 1 mph greater than for five-minute intervals with low AI (< 8). This difference was not statistically significant. Mean reduction for five-minute intervals when work was within 6 ft of the travel lane was approximately 6 mph higher than all other five-minute intervals. This difference was statistically significant. For distances less than 12 feet from the travel lane, a 3-foot shift in work activity away from the travel lane resulted in a speed increase of 2 mph.

Mean speed reduction for five-minute intervals with high flow rates (> 100 vehicles) was approximately 10.5 mph greater than at sites with lower flow rates. Five-minute intervals with low flow rates (< 100 vehicles) exhibited an increase in mean speeds in the presence of work activity. Mean speed reduction for five-minute intervals with truck percentage greater than 10 percent were higher than for lower truck percentages.

Benekohal et. al. developed models for work zone operating speed and capacity using data from 11 work zones on four-lane Interstate highways in Illinois [**34**]. Three of the work zones were characterized as short-term. One lane was closed to accommodate work activity at all of the work zones. Headways, volumes, speeds, and queue characteristics were collected with video equipment. The lack of a comprehensive dataset resulted in the application of *HCM* values and subjective judgments at some stages of model development.

A methodology was developed to estimate work zone free-flow speeds. The basic structure was similar to free-flow speed estimation in the *Highway Capacity Manual* (*HCM*) [**38**]:

Eq. **2.1**

$$U_{FF} = BFFS - R_{WI} - R_{LW} - R_{LC} - R_O \qquad \textbf{2.1}$$

where: U_{FF} = estimated free-flow speed (mph)

$BFFS$ = base free-flow speed (if no information exists, assume to be 5 mph greater than the posted speed limit) (mph)

R_{WI} = reduction in free-flow speed due to work intensity (mph)

R_{LW} = reduction in free-flow speed due to lane width (use *HCM 2000* adjustments for freeways) (mph)

R_{LC} = reduction in free-flow speed due to lateral clearance (use *HCM 2000* adjustments for freeways) (mph)

R_O = reduction in free-flow speed due to all other factors (if information exists) (mph)

Work intensity was characterized by the number of workers and pieces of construction equipment and their proximity to the open travel lane. The following relationship was used:

Eq. **2.2**

$$WI_r = \frac{w+e}{p} \qquad \textbf{2.2}$$

where: WI_r = work intensity ratio

w = number of workers in active work area (integer from 0 to 10)

e = pieces of equipment in active work area (integer from 0 to 5)

p = distance between active work area and open travel lane (varies from 1 to 9 feet)

The work intensity ratio was used to estimate the work intensity reduction factor (R_{WI}) in Eq. **2.1**. The relationship between R_{WI} and work intensity ratio was developed using driver surveys for short-term work zones and field data for long term work zones. The following equations were proposed:

Eq. **2.3**

Short-term work zones: $R_{WI} = 11.918 + 2.6766\ln(WI_r)$ **2.3**

Eq. **2.4**

Long-term work zones: $R_{WI} = 2.6625 + 1.2056\ln(WI_r)$ **2.4**

A validation effort showed the methodology reasonably predicted speeds and capacities. However, the same work zones used for model development were used for validation.

2.3 Summary of Work Zone Speed Literature

Two work zone speed philosophies were identified: maintain normal highway speeds or reduce traffic speeds from pre-work zone or upstream conditions. Existing guidance in the *MUTCD* as well as recommended work zone design procedures combined both philosophies into a general approach: maintain speeds at or near normal speeds if practical; if speed reductions are necessary, minimize the magnitude of the reduction and notify the driver with “consistent, credible and complimentary information sources" [**21**]. A maximum speed reduction of 10 mph was considered desirable based on results by Migletz et. al. showing that this level resulted in the smallest increase in speed variance [**20**]. Two observations were noted:

- Existing and proposed design and traffic control practices are based on achieving desirable speed magnitudes while minimizing speed variance, objectives that may be conflicting or complimentary depending on the design or traffic control decision.
- Recommendations based on research results for posted speed have been applied to other speed measures (e.g. design speed, target speed); these measures may or may not be surrogates for actual operating speeds.

Current and recommended work zone design processes would benefit from an understanding of the speed related outcomes of design and traffic control decisions. A literature review demonstrated that knowledge in this area is limited.

Ten studies were identified that investigated the speed effects (i.e. speed magnitude and speed variance) of general design decisions and features common to most work zones. The work zone features included:

- Advisory and regulatory speed signing;
- Channelizing devices;
- Work zone location;
- Work zone type;
- Length of TLTW sections in median crossover work zones;
- Median crossovers design;
- Lane width; and
- Work activity.

Only three of the ten studies collected data in more than four work zones. Both larger and smaller studies were focused on one or two specific work zone features and did not collect or control for other possible speed-influencing variables. The smaller sample sizes and large portions of unexplained variation resulted in a lack of rigorous statistical testing and findings. An example illustrating this assessment was provided by Migletz et. al. from a study that is one basis for current work zone posted speed guidance in the *MUTCD* [**20**]:

> “However, an important caveat…is that none of the differences between the percent increases in speed variance…are statistically significant. Although disappointing, this finding reflects the conditions inherent in work zones…Given that motorist responses are so highly variable, it is unlikely that statistically significant differences can be found.”

No work zone speed models were identified. A speed model is defined in this research as a regression equation that relates a measure of speed (e.g. mean, 85th percentile, individual vehicle) as a left-hand-side (LHS) variable to a number of explanatory, or right-hand-side (RHS) variables and a set of estimated parameters. Common RHS variables are roadway and roadside geometrics, presence and type of traffic control and traffic characteristics. An example is provided below in Eq. **2.5** [**39**].

Eq. **2.5**

$$V(85) = 41.62 - 1.29(D) + 0.0049(L) - 0.12(I) + 0.95(V_t) \qquad \textbf{2.5}$$

where: $V(85)$ = expected 85th percentile speed on horizontal curves (km/h)

D = degree of curve (degrees per 30m of arc)

L = length of curve (m)

I = deflection angle (degrees)

V_t = measured 85th percentile speed on approach tangent (km/h)

Speed models have been commonly used to investigate speed effects of roadway and traffic control features in permanent roadway environments. These studies were identified and reviewed, with particular focus on speed model estimation techniques. A majority of studies specified a single equation, linear-in-parameters model and used the ordinary least squares (OLS) estimator ([**40**] through [**51**]). A smaller number of studies estimated speed models with panel data approaches ([**52**] and [**53**]) and simultaneous equation estimators ([**54**] and [**55**]). The work by Shankar and Mannering [**54**] was a catalyst for methods investigated and discussed in Chapters **3**, **4** and **5**.

Chapter 3
Data and Methodology

This chapter defines the research scope and general modeling philosophy. Specifically, it addresses:

- Data collection scope and methods;
- Definitions and descriptive statistics of variables;
- Characterization of data and identification of modeling techniques; and
- Modeling philosophy and model estimation.

3.1 Scope

The *MUTCD* defines a work zone as an area of highway with construction, maintenance, or utility work activities [**1**]. The type and magnitude of work zone activities, work zone features, traffic control devices and potential impacts on the transportation system is related to work zone duration. Five categories of duration are recognized [**1**]:

1. *Long-term stationary* is work that occupies a location for more than 3 days.
2. *Intermediate-term stationary* is work that occupies a location for more than one daylight period up to 3 days, or nighttime work lasting more than 1 hour.
3. *Short-term stationary* is daytime work that occupies a location for more than 1 hour within a single daylight period.
4. *Short duration* is work that occupies a location for up to 1 hour.
5. *Mobile* is work that moves intermittently or continuously.

This research focused on construction work zones, locations of long-term stationary work for the purpose of construction, reconstruction, rehabilitation or preventive maintenance. A number of work zone traffic control strategies exist. The feasibility of specific strategies is dependent on facility type; a large number of facility type-work zone strategy combinations are possible (e.g., see [**21**]). In addition, speed data may be collected under a variety of conditions (e.g., day, night, clear weather, rain, congested, free-flow conditions etc.). The following sections define the data collection scope with regard to work zone strategy, facility type, vehicle type and operating and environmental conditions.

3.1.1 Work Zone Strategy and Facility Type

All work zones were either a lane closure or median crossover located on a four-lane divided freeway. These are commonly occurring work zone strategies and the focus of a majority of the literature summarized in Chapter **2**. The following definitions apply [**21**]:

- *Lane closure:* a construction work zone type for which one or more travel lanes and any adjacent shoulders are closed to traffic. On four-lane divided highways, the closure is either the outside lane and shoulder or the median lane and shoulder, with traffic using all or part of the remaining open lane and shoulder.
- *Median crossover:* a construction work zone type used on expressways and freeways wherein:
  - the number of lanes in both directions are reduced;
  - traffic in one direction is routed across the median to the opposite-direction roadway on a temporary roadway constructed for that purpose; and
  - bi-directional traffic is maintained on one roadway while the opposite direction roadway is closed.
- *Four-lane divided freeway:* A divided facility with two-lanes per direction and full control of access (i.e. access provided only through grade separated interchanges).

Example plans and cross sections for typical lane closures and median crossovers on four-lane divided freeways are illustrated in Figure **3-1** through Figure **3-4**. All freeways were located in either Pennsylvania (PA) or Texas (TX) and had pre-work zone posted speeds ranging from 55 to 70 mph. A summary of each work zone site, including strategy type and pre-work zone posted speed is provided in Table **3-1**.

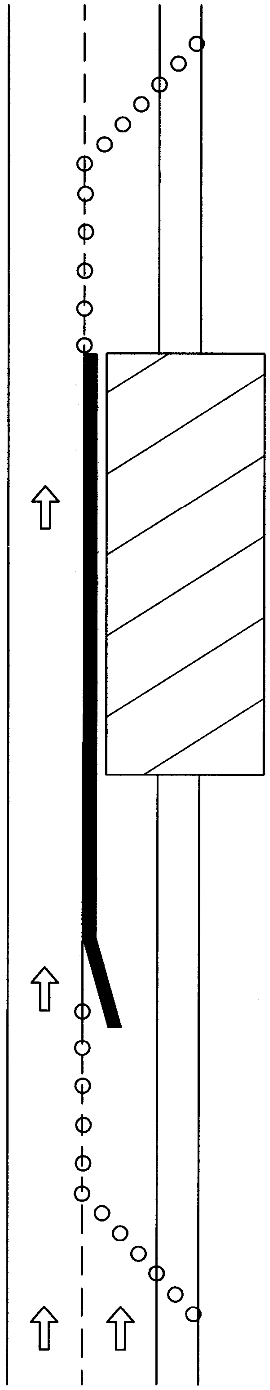

Figure **3-1**: Example plan for lane closure

Figure **3-2**

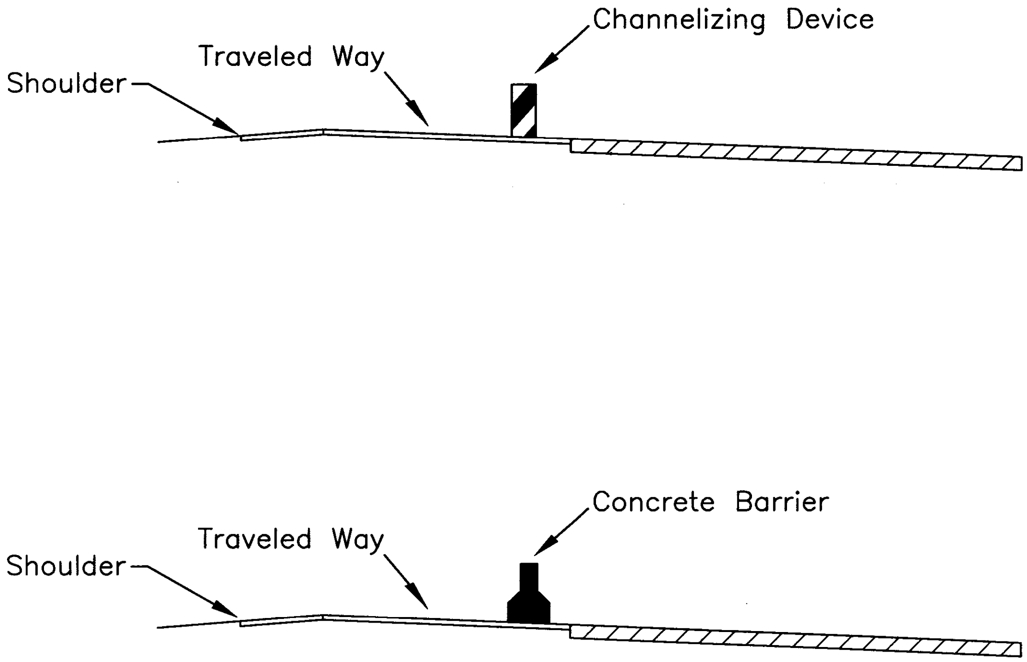

Figure **3-2**: Example cross sections for lane closure

Figure **3-3**

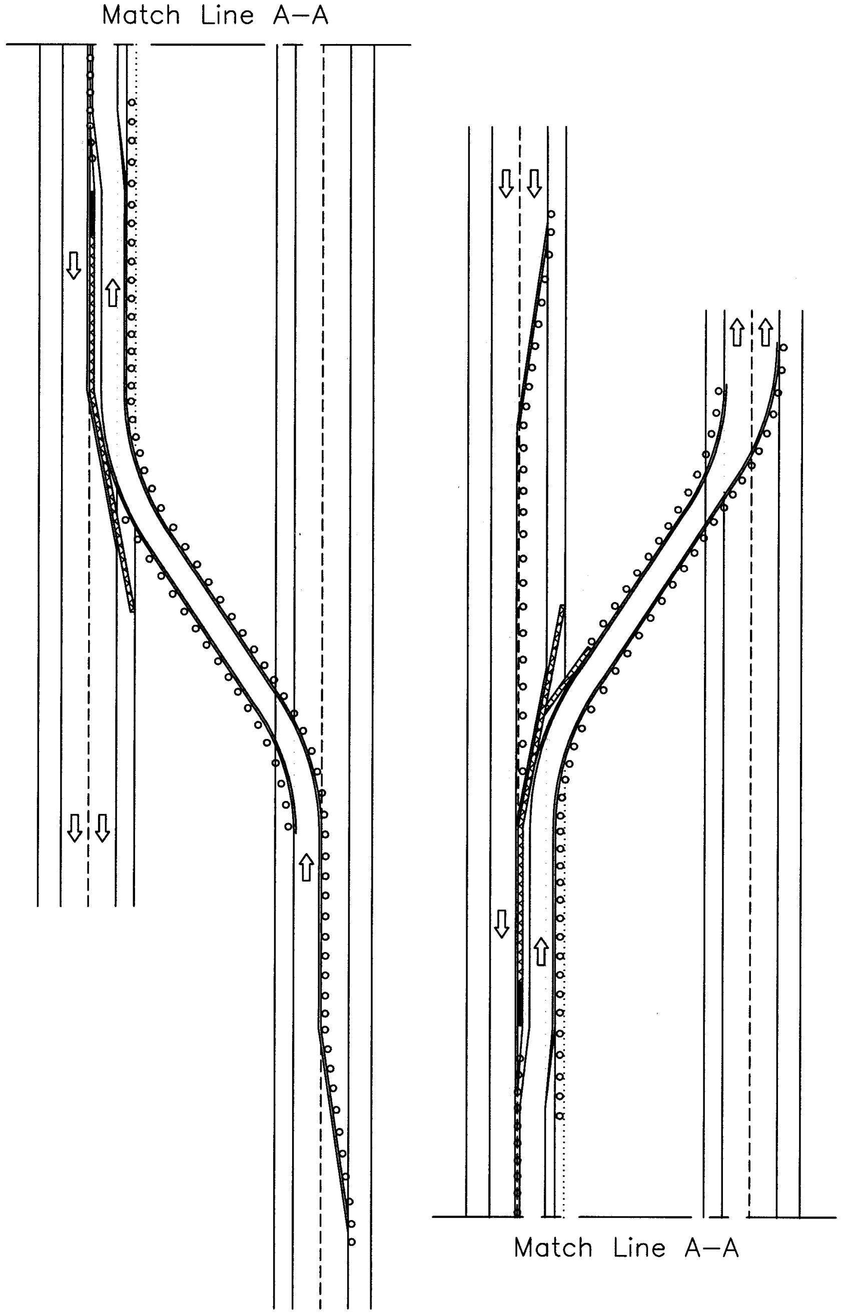

Figure **3-3**: Example plan for median crossover

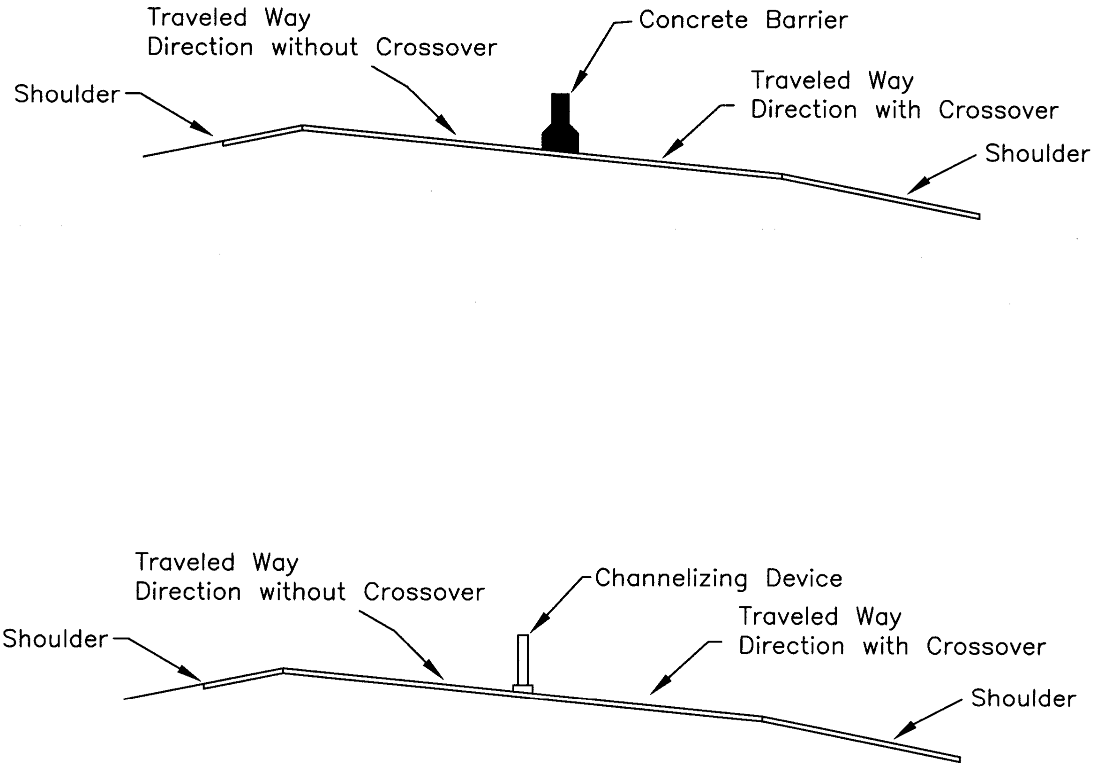

Figure **3-4**: Example cross sections for TLTW traffic on normally divided facility resulting from median crossover

Table **3-1**

Table **3-1**: Summary of work zone location, type and pre-work zone posted speed

Site	Work zone strategy	Pre-work zone posted speed
Interstate 80 Westbound; Lanse, PA	Median crossover	65 mph
Interstate 80 Westbound; Clearfield, PA	Median crossover	65 mph
Interstate 80 Westbound; Limestoneville, PA	Lane closure	65 mph
Interstate 80 Westbound; Lime Ridge, PA	Lane closure	65 mph
Interstate 180 Eastbound Extension / PA 147; Watsontown, PA	Median crossover	65 mph
Interstate 180 Westbound; Muncy, PA	Lane closure	65 mph
Interstate 180 Eastbound; Muncy, PA	Lane closure	65 mph
Interstate 380 Southbound; Gouldsboro, PA	Lane closure	65 mph
Interstate 380 Northbound; Gouldsboro, PA	Lane closure	65 mph
Interstate 80 Eastbound; Limestoneville, PA	Lane closure	65 mph
Interstate 10 Eastbound; Waelder, TX	Lane closure	70 mph
Interstate 20 Eastbound; Santo, TX	Median crossover	60 mph
Interstate 20 Westbound; Santo, TX	Median crossover	70 mph
Interstate 35 Northbound; Sanger, TX	Lane closure	65 mph
Interstate 45 Northbound; Huntsville, TX	Lane closure	70 mph
Interstate 45 Southbound; Angus, TX	Median crossover	70 mph
Loop 288; Denton, TX	Lane closure	55 mph

3.1.2 Vehicle Type

Both passenger cars and trucks were observed. Passenger cars were defined as vehicles having four tires in contact with pavement and included cars, pickup and single unit trucks, vans and sport utility vehicles. Vehicles with more than four tires in contact with pavement were classified as trucks. Passenger cars and trucks were collected as they appeared in the traffic stream during the observation period (i.e. there was not a criterion to collect a certain percentage of passenger cars or trucks). A summary of sample sizes for each vehicle type by work zone is provided in Table **3-2**.

Table **3-2**

Table **3-2**: Summary of sample sizes for each vehicle type by work zone

Site	Number of passenger cars observed	Number of trucks observed
Interstate 80 Westbound; Lanse, PA	886	828
Interstate 80 Westbound; Clearfield, PA	887	804
Interstate 80 Westbound; Limestoneville, PA	556	428
Interstate 80 Westbound; Lime Ridge, PA	165	28
Interstate 180 Eastbound Extension / PA 147; Watsontown, PA	732	268
Interstate 180 Westbound; Muncy, PA	757	243
Interstate 180 Eastbound; Muncy, PA	735	265
Interstate 380 Southbound; Gouldsboro, PA	460	151
Interstate 380 Northbound; Gouldsboro, PA	398	202
Interstate 80 Eastbound; Limestoneville, PA	762	638
Interstate 10 Eastbound; Waelder, TX	1011	589
Interstate 20 Eastbound; Santo, TX	2023	1577
Interstate 20 Westbound; Santo, TX	2015	1331
Interstate 35 Northbound; Sanger, TX	735	240
Interstate 45 Northbound; Huntsville, TX	593	207
Interstate 45 Southbound; Angus, TX	1249	751
Loop 288; Denton, TX	868	132
Total	14832	8682

3.1.3 Operating and Environmental Conditions

All data were collected during daylight hours in dry conditions. Volume-to-capacity ratios were low enough that no queue formation occurred at any location in the work zone. Observing free-flow vehicles was desired, which theoretically occurs when the flow rate approaches zero. For practicality of data collection, free-flow has been defined using flow or headway criteria. For example, the *HCM* recommends data collection for free-flow speed determination on two-lane rural roads when two-way flow rates are less than 200 passenger cars per hour. For this study, a free-flow passenger car or truck was defined as one having a time headway greater than 4 seconds to the preceding vehicle.

3.2 Work Zone and Infrastructure Data

Candidate explanatory variables in the speed models included work zone geometry (i.e. alignment, cross section, roadside) and temporary traffic control. Work zone geometry included geometry of the permanent infrastructure at the work zone location. Sources of this data for the locations listed in Table **3-1** were as-built plans/drawings located in Pennsylvania and Texas Departments of Transportation (DOT) district offices, temporary traffic control plans located in DOT project offices and observations and measurement made at the construction sites. A typical protocol for work zone and infrastructure data collection involved the following steps:

1. Videotape a drive through of the subject work zone and record (vocally) notes of general geometric and traffic control observations.
2. Using video and notes, select potential data collection locations based on obtaining a representative range of geometry in the work zone.
3. Collect speed data and record geometric and traffic control observations at selected locations.
4. Determine data collection locations in reference to the nearest mile marker.
5. Collect relevant geometric and traffic control information from temporary traffic control plans in state DOT project field office and verify with field observations made in step 3.
6. Determine geometrics of permanent infrastructure at work zone location from as-built plans in state DOT district offices and verify with field observations made in step 3.

For each of the 17 work zones, at least one data collection location was located in the lane taper, defined as the area of transition between the normal/upstream cross section and the work zone cross section using a series of channelizing devices and pavement markings. Other locations were in the activity area, defined as the area from the end of the lane taper to the end of the work zone. The number of lane taper and activity area locations by state and traffic control strategy is provided in Table **3-3**. The total number of vehicle observations for each location is also provided.

Table **3-3**

Table **3-3**: Number of data collection locations and vehicle observations by state and work zone strategy

State	Lane Closure						Median crossover					
	Taper			Activity Area			Taper			Activity Area		
	Number of Data Collection Locations	Number of Passenger Vehicle Observations	Number of Truck Observations	Number of Data Collection Locations	Number of Passenger Vehicle Observations	Number of Truck Observations	Number of Data Collection Locations	Number of Passenger Vehicle Observations	Number of Truck Observations	Number of Data Collection Locations	Number of Passenger Vehicle Observations	Number of Truck Observations
PA	6	826	378	23	3007	1577	2	215	185	21	2290	1715
TX	11	1598	577	11	1609	591	4	475	325	41	4812	3334
Total	17	2424	955	34	4616	2168	6	690	510	62	7102	5049

The following geometric and traffic control information was collected at all locations:

- Travel lane width;
- Right and left shoulder width;
- Right and left shoulder type;
- Presence of and offset to roadside objects (e.g. temporary or permanent barrier, work zone channelizing devices, other roadside conditions);
- Radius of horizontal curves;
- Vertical grade;
- Rate of vertical curvature;
- Posted speed limit;
- Distance from the lane taper; and

- Cross slope.

Observed frequencies of the categorical variables by work zone location are summarized in Table **3-4** . Ranges, means and standard deviations of the continuous variables are in Table **3-5**.

Table **3-4**

Table **3-4**: Descriptive statistics of categorical work zone variables

		Lane Taper (23 locations)		**Activity Area (96 locations)**	
Variable	**Categories**	**Frequency**	**Percent**	**Frequency**	**Percent**
Lane closed	Left	7	30.4%	9	9.4%
	Right	16	69.6%	87	90.6%
Posted speed	50	4	17.4%	25	26.0%
	55	2	8.7%	8	8.3%
	60	4	17.4%	31	32.3%
	65	7	30.4%	16	16.7%
	70	6	26.1%	16	16.7%
Police presence	no	21	91.3%	92	95.9%
	yes	2	8.7%	4	4.2%
Roadway type	Permanent	23	100.0%	66	68.8%
	Temporary	0	0.0%	30	31.3%
Horizontal alignment	Tangent	19	82.6%	52	54.2%
	Curve to the left	2	8.7%	27	28.1%
	Curve to the right	2	8.7%	17	17.7%
Vertical alignment	Flat (-1 to 1)	12	52.2%	41	42.7%
	Upgrade	2	8.7%	21	21.9%
	Downgrade	1	4.3%	25	26.0%
	Crest curve	7	30.4%	4	4.2%
	Sag curve	1	4.3%	5	5.2%
Location in vertical curve	Incoming grade	2	8.7%	0	0.0%
	Middle	1	4.3%	5	5.2%
	Outgoing grade	1	4.3%	2	2.1%
	N/A	15	65.2%	87	90.6%
	Missing	4	17.4%	2	2.1%
Traffic control device in the left roadside	None	15	65.2%	31	32.3%
	Drum	7	30.4%	7	7.3%
	Panel	0	0.0%	2	2.1%
	Guardrail	0	0.0%	4	4.2%
	Concrete barrier	1	4.3%	50	52.1%
	Opposing traffic	0	0.0%	2	2.1%
Traffic control device in the right roadside	None	7	30.4%	36	37.5%
	Drum	8	34.8%	17	17.7%
	Panel	1	4.3%	9	9.4%
	Guardrail	0	0.0%	9	9.4%
	Concrete barrier	4	17.4%	20	20.8%
	Other	3	13.0%	5	5.2%

Table **3-5**

Table **3-5**: Descriptive statistics of continuous work zone variables

	Lane Taper (23 locations)					**Activity Area (96 locations)**				
Variable	**N**	**Min**	**Max**	**Mean**	**Std**	**N**	**Min**	**Max**	**Mean**	**Std**
Downstream distance from end of lane taper (miles)	23	0	0.2	0.06	0.08	96	0.2	10.6	3.03	3.03
Radius of curve (ft)	4	2292	7640	4018	2448	44	1911	11480	5743	3198
Superelevation (%)	22	2	7.5	2.46	1.48	81	2.0	7.5	2.56	1.43
Incoming grade (%)	22	-3.22	3	0.39	1.35	96	-4.0	3.0	-0.33	1.77
Outgoing grade (%)	5	-3.5	-2	-2.96	0.61	7	-2.7	3.0	-0.18	2.41
K(1) (ft/%)	7	247	615	364	127	9	150	500	258	128
Traveled way width (ft)	23	12	24	17	4.6	96	11	16	12.44	1.29
Right shoulder width (ft)	23	0	10	3	4.6	96	0	16	4.17	4.10
Left shoulder width (ft)	23	0	8	3.7	3	96	0	36	3.23	4.40
Total paved width (ft)	23	16	34	23	5.3	96	12	48	19.14	4.89
Left offset to TCD(2) (ft)	8	0	5	1.1	1.8	65	0	48	3.91	9.44
Right offset to TCD (ft)	16	0	4	1.3	1.4	60	0	24	2.78	3.79

(1) K = rate of vertical curvature
(2) TCD = traffic control device

3.3 Selection of Data Collection Equipment

Development of a speed data collection protocol was based on five factors:

1. Data collection capabilities versus cost;
2. Accuracy of speed measurements;
3. Effects on driver behavior;

4. Disruption to traffic patterns and construction activity during equipment installation and use; and
5. Required manpower for data collection and reduction.

Data collection capabilities versus cost refer to the ability of the equipment to collect and record data that maximizes the potential of meeting the research objectives at a reasonable cost. From the perspective of minimizing random error and maximizing the number of potential analysis techniques, the following (from most desirable to least desirable) alternatives existed:

- Continuously track individual vehicle speed through the work zone;
- Track vehicle speed through the work zone by recording speeds at a finite number of locations;
- Collect samples of vehicle speeds at a finite number of locations knowing all or a large percentage of the sample are the same vehicles in samples at other locations; or
- Collect independent samples of vehicle speeds at a finite number of locations.

Accuracy of speed measurements is the level of agreement between the actual observed speeds and measured speeds. A high level of accuracy was desired. If measurements were not accurate, it was desirable that the errors were random and small with a zero mean or that they were known and systematic and could be corrected for.

Ideally, presence of data collection equipment would have no effect on motorist speed behavior including speed magnitudes, acceleration/deceleration characteristics, and variability within a sample of traffic. It was unlikely that the effects would be zero for all observations as some drivers may detect the presence of equipment and decrease their speed. The goal of the selected data collection protocol was to minimize these effects.

Equipment installation and use would either require encroachment into the roadway (i.e. traveled way and/or shoulders), utilize only roadside areas (i.e. beyond the shoulder) or a combination of both. It was desired that disruption to traffic patterns and construction activity during equipment installation and data collection be avoided. It was also desired that required man-hours for equipment installation and data collection, reduction and preparation be cost effective.

Six data collection methods were evaluated using these criteria:

- Light Detection and Ranging (LIDAR);

- Magnetic sensor;
- Manual/video observation;
- Pneumatic tubes;
- Radio Detection and Ranging (RADAR); and
- Tapeswitches.

Table **3-6** provides a summary of the evaluation, partially based on results presented by Antonucci et. al. [**56**].

Table **3-6**

Table **3-6**: Evaluation of data collection equipment

	Data collection capabilities and cost	Accuracy of speed measurements (1)	Effects on driver behavior (1)	Disruption to traffic patterns and construction activity during installation and data collection	Required manpower for data collection and reduction
Light Detection and Ranging	◘	●	●	●	●
Magnetic sensor	●	◘	●	○	●
Manual/video observation	●	◘	●	●	◘
Pneumatic tubes	●	◘	◘	○	◘
Radio Detection and Ranging	◘	●	●	●	●
Tapeswitches	◘	●	◘	○	◘

● = best alternative for meeting criteria
◘ = meets criteria, but is not best alternative
○ = does not meet criteria
(1)based on findings from Antonucci et. al. [**56**]

Three alternative equipment choices did not meet all criteria (magnetic sensor, pneumatic tubes and tapeswitches). Each of these required intrusions into the traveled way for installation and removal and temporary lane closures would be needed. This was not practical given the primarily-Interstate facility types and corresponding volumes, speeds and the capacity reduction already present as a result of the construction activities.

LIDAR, RADAR and manual observations have the capabilities to either:

- Track vehicle speed through the work zone by recording speeds at a finite number of locations;
- Collect samples of vehicle speeds at a finite number of locations knowing all or a large percentage of the sample are the same vehicles in samples at other locations; or
- Collect independent samples of vehicle speeds at a finite number of locations.

Of these, manual observation was the least costly option; however, LIDAR and RADAR are more accurate and required less manpower for data collection set up and data reduction. Both LIDAR and RADAR were used for data collection.

3.4 Speed Data

The project budget for equipment purchase and manpower was not large enough to track individual vehicle speeds or samples of the same vehicles through the work zone using LIDAR and RADAR. Independent samples of vehicle speeds were measured at a finite number of locations (see **3.2** for discussion on how locations were selected). Approximately 200 free-flow speeds were collected at each location. Determination of whether the observed vehicle was free-flow (see definition in **3.1.3**) was made manually.

Data collectors concealed themselves from the view of drivers to avoid influencing vehicle speeds by their presence. In most cases, data collectors positioned themselves upstream of the desired location. Speeds were measured as vehicles passed the selected location and drove away from the data collector. RADAR was used when the smaller beam of LIDAR was not practical given the location of the data collector relative to traffic. At these locations, cosine corrections to the observed speeds were made to account for angular differences between the vector of RADAR measurement and the vector of vehicle movement. The LIDAR unit automatically made cosine corrections. The RADAR was turned off until the moment of speed measurement to try and minimize the effects on drivers with RADAR-detecting equipment.

Over 23,500 free-flow speeds were collected at 119 locations (see Table **3-3**) in 17 work zones. At each work zone, 200 free-flow speeds were also collected approximately one to two miles upstream of the advance warning area. Investigating properties of these upstream speeds as potential explanatory variables of work zone speeds is discussed in **4.2** and **5.5**. Speed data at each location was aggregated onto a measure of speed magnitude (85th percentile speed) and a measure of speed dispersion (standard deviation of speed). Descriptive statistics for these speed measures are summarized in Table **3-7** and Table **3-8**.

Table **3-7**

Table **3-7**: Descriptive statistics of 85th percentile speed (aggregated by location)

	Aggregated 85th percentile Speed for All Vehicles (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	57	74	66.00	5.70
Activity Area	96	44	72	61.11	5.11
	Aggregated 85th percentile Passenger Car Speed (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	57	76	66.81	5.85
Activity Area	96	43	73	61.71	5.24
	Aggregated 85th percentile Truck Speed (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	55	70	63.16	5.06
Activity Area	96	44	68	60.10	4.95

Table **3-8**

Table **3-8**: Descriptive statistics of standard deviation of speed (aggregated by location)

	Aggregated Standard Deviation of Speed for All Vehicles (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	4.17	6.60	5.49	0.552
Activity Area	96	2.79	8.33	4.70	0.940
	Aggregated Standard Deviation of Passenger Car Speed (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	4.45	6.68	5.46	0.648
Activity Area	96	2.81	8.61	4.83	0.959
	Aggregated Standard Deviation of Truck Speed (mph)				
Location	N	Minimum	Maximum	Mean	Std. Deviation
Lane Taper	23	3.49	6.40	4.89	0.866
Activity Area	96	2.18	7.82	4.27	0.972

3.5 Characterization of Data and Identification of Modeling Techniques

Selection of appropriate analysis techniques is dependent on the characteristics of the data and research objectives. A majority of work that has attempted to link traffic operations with infrastructure and other environmental factors used data from observational studies. In an observational study, data that can be "found" or collected is interpreted. There is normally no control over observed and unobserved factors that may influence variables of interest. This is quite different than controlled experiments, often conducted in other fields of science (e.g. agriculture, medicine), where the effects of a few factors are observed by controlling or diluting influences from other variables through experimental design procedures. Given these distinctions, data from observational studies are often referred to as non-experimental data.

The data described in **3.2** through **3.4** are from an observational study. Depending on the interpretation of "time," the data may be viewed as cross-sectional or pooled cross-section and time series data (i.e. panel data). The techniques that were identified to estimate models of speed magnitudes and deviations treated the data primarily as cross sectional. These included:

- Ordinary least squares regression;
- Seemingly unrelated regression estimation;
- Limited-information simultaneous equation models; and
- Full-information simultaneous equation models.

The remainder of this chapter includes a general discussion of econometric modeling philosophy and estimation.

3.6 Modeling Philosophy

A review of applied econometrics literature will show much attention paid to model estimation and hypotheses testing within a given model specification. Little time is spent on the specification itself. A major reason is that specification is both philosophically and practically difficult and complicated. The following observations provide useful starting points for this discussion:

"Econometric models are 'false'…there is no hope, or pretense, that through them the 'truth' will be found." [**57**]

“In practice all econometric specifications are necessarily ‘false’ models…a useful model is not one that is ‘true’ or ‘realistic’ but one that is parsimonious, plausible and informative.” [**58**]

If this is indeed the case, a reasonable question is “why model”? The philosophy adopted by this research was that econometric models provide a way to gain or increase understanding of complex phenomena by drawing associations between variables (endogenous and exogenous; observed and unobserved) in a system. They may be used in some cases to test theory, in others to develop theory. Useful econometric models are those that tell the most complete and accurate story using the facts (i.e. data) at hand.

There is no general consensus in applied econometrics literature on how best to determine the correct specification. Practice ranges from formal statistical testing to determine whether to include or exclude variables to innovative and imaginative techniques that are difficult to describe and usually are not. Kennedy organized specification methodologies into three approaches: average economic regression (AER), test-test-test (TTT) and fragility analysis and provides seven general specification principles [**57**]. Econometrics texts discuss the implications of simple-to-general and general-to-simple specifications (e.g., [**59**] and [**60**]). Other areas of debate include specifications based solely on theory versus data mining, the role of statistical significance in model specifications, and model simplicity.

This research will not attempt to solve these philosophical debates; however, it is important to recognize they exist and understand the context in which a model is built (e.g. modeling, forecasting, theory-testing, or policy). As some have noted, it may be most desirable to blend the differing viewpoints (e.g., [**61**]). This view was supported by this research as indicated by the general modeling strategies that were used:

- Specifications that combined theory, common sense, previous findings as well as the characteristics of the data set were tested.
- A general-to-specific strategy was used in a sense that all variables related to traffic control and the infrastructure were thought to possibly be associated with speed magnitudes and deviations.

- Initial specifications were not completely general to include all possible lags and interactions; the focus was main effects.
- Statistical significance (i.e. probability of a Type I error) of a specific level and model fit were used to guide specifications, but application was not strict (i.e. including only RHS variables with t-statistics above a pre-determined threshold and maximizing R-squared were not controlling strategies). This strategy likely minimized the probability of a Type II error.
- Consistency of parameter magnitudes and signs across different specifications and divisions of the data set guided final specifications.
- Model simplicity was desired, but not as an equal trade-off to illustrating a complete picture of the data.

The models are intended to discover possible associations between work zone variables and vehicle speeds. In the absence of other information, they may also be used for forecasting or policy development. Results and conclusions will be presented in a way amendable to all three applications.

3.7 Model Estimation

Models consist of endogenous and exogenous variables. Distinctions between the two are sometimes subtle and have been the subject of a large body of literature [**60**]. Endogenous variables are synonymous with dependent variables, determined jointly in time period *t* and dependent on the values of explanatory variables. Exogenous variables are synonymous with independent variables, varying independently of other variables in time period *t*. Endogenous variables can be explained by both endogenous and exogenous RHS variables. Specifications with only exogenous RHS variables are the focus of Chapter **4**. Specifications with exogenous and endogenous RHS variables are addressed in Chapter **5**.

For reasons discussed in **1.4**, the endogenous speed variables of interest are:

- 85th percentile free-flow speed of passenger cars;
- 85th percentile free-flow speed of trucks;
- Speed deviation of passenger cars; and
- Speed deviation of trucks.

The general system structure is:

Eq. **3.1**

$$s_c = \alpha_{sc} + X_{sc}\beta_{sc} + Z_{sc}\gamma_{sc} + \varepsilon_{sc} \quad \textbf{3.1}$$

Eq. **3.2**

$$s_t = \alpha_{st} + X_{st}\beta_{st} + Z_{st}\gamma_{st} + \varepsilon_{st} \quad \textbf{3.2}$$

Eq. **3.3**

$$d_c = \alpha_{dc} + X_{dc}\beta_{dc} + Z_{dc}\gamma_{dc} + \varepsilon_{dc} \quad \textbf{3.3}$$

Eq. **3.4**

$$d_t = \alpha_{dt} + X_{dt}\beta_{dt} + Z_{dt}\gamma_{dt} + \varepsilon_{dt} \quad \textbf{3.4}$$

where: s_c = 85th percentile free-flow speed of passenger cars

s_t = 85th percentile free-flow speed of trucks

d_c = speed deviation of passenger cars

d_t = speed deviation of trucks

X_{sc} = exogenous variables related to s_c

X_{st} = exogenous variables related to s_t

X_{dc} = exogenous variables related to d_c

X_{dt} = exogenous variables related to d_t

Z_{sc} = endogenous variables related to s_c (may include s_t , d_c , and d_t)

Z_{st} = endogenous variables related to s_t (may include s_c , d_c and d_t)

Z_{dc} = endogenous variables related to d_c (may include s_c , s_t and d_t)

Z_{dt} = endogenous variables related to d_t (may include s_c, s_t and d_c)

α, β, γ = regression parameters to be estimated

ε = disturbance term

General methods used for specification of the RHS variables (i.e. X and Z) were discussed in **3.6**. The remainder of this section discusses principles for finding the "best" estimates of the regression parameters α, β and γ. The summary below was adapted from [**59**] but can be found in most econometric textbooks.

The four structural equations represent data generating processes for the speed measures of interest. The parameters α, β and γ are the true average relationship between the LHS and RHS variables. These true parameters are constants, but can never be known unless data for the entire population of work zones and drivers are collected. However, estimates of α, β and γ (*a*, *b* and *g*, respectively) can be obtained by using sample regression techniques. The parameter estimates *a*, *b* and *g* are random variables (i.e. they are a function of the observations in the sample and will be different for other samples). Parameter estimates are obtained from mathematical functions of the data known as estimators.

The most important step of estimation involves selection of the "best" estimator for a given specification. Several factors are used to make this determination:

- Unbiasedness;
- Efficiency;
- Mean squared error (MSE); and
- Asymptotic properties.

Descriptions of these properties, which will be referenced throughout the remainder of this dissertation, are provided below. Estimators that meet small-sample criteria (i.e. are unbiased and efficient) are desirable, but not always available. If this is the case, the asymptotic properties (described in points 5 and 6) are adopted.

1. An estimator of *b* is an unbiased estimator of β if $E(b) = \beta$. If this does not hold, then the estimator is biased by $E(b) - \beta$.

2. If b_1 and b_2 are estimated using two unbiased estimators for β and $Var(b_1) < Var(b_2)$ then the estimator for b_1 is more efficient than the estimator for b_2.
3. The estimator that is linear and unbiased and has minimum variance among all linear unbiased estimators is called the *Best Linear Unbiased Estimator* (BLUE).
4. The mean square error (MSE) of an estimator is defined as $E\left[(b-\beta)^2\right]$, which is the same as the sum of the variance and the squared bias. The MSE is useful in assessing trade-offs between bias and variance. If b_1 and b_2 are estimated using two estimators for β and $MSE(b_1) < MSE(b_2)$ then the estimator for b_1 is mean squared efficient compared to b_2.
5. An estimator of b is a consistent estimator of β if $\lim_{n\to\infty} P(\beta - \varepsilon \le b \le \beta + \varepsilon) = 1$ for all $\varepsilon > 0$ (where n is the sample size). As the sample size increases, $Var(b)$ decreases and b converges to β.
6. A consistent estimator of b_1 is asymptotically efficient if for every other consistent estimator (e.g. b_2) $\lim_{n\to\infty}\left[\frac{Var(b_1)}{Var(b_2)}\right] < 1$ for all β. The variance of an efficient estimator approaches zero the fastest and therefore, the estimate of b converges to β the fastest.

The ordinary least squares estimator is the BLUE under a given set of circumstances or assumptions summarized in **4.1** . Depending on the research questions being addressed by the models, some assumptions may be more important than others. Given its computational ease and relative robustness, the OLS estimator is normally investigated first, with formal checks of whether the desirable circumstances making it the BLUE hold. If not, alternative estimators are identified and evaluated.

Chapter 4
Ordinary Least Squares and Seemingly Unrelated Regression Models

This chapter summarizes model specifications and estimations with only exogenous RHS variables (e.g. work zone geometry and traffic control). Estimator details, relevant hypothesis testing and estimation results are provided for:

- Ordinary least squares (OLS) regression;
- Seemingly unrelated regression (SUR); and
- First-order autoregressive (AR1) models.

The chapter concludes with a summary of statistical findings.

4.1 Ordinary Least Squares Regression Models

The most commonly used estimator in applied econometrics is OLS [**59**]. Depending on the properties of the data and the research questions being addressed, OLS often serves only as a departure point for full analysis [**60**]. However, in many cases it may also provide comparable insights into empirical questions as more computationally intensive estimations. It was a practical starting point for estimating the parameters of Eq. **3.1** through Eq. **3.4**.

In order to discuss the important details of the OLS estimator, Eq. **3.1** through Eq. **3.4** are further generalized by:

Eq. **3.1**

$$y = X\beta + \varepsilon \qquad \mathbf{4.1}$$

where: y = n x 1 matrix of some speed measure (s_c , s_t , d_c or d_t);

X = n x k matrix of variables influencing y ;

β = k x 1 matrix of parameters quantifying the relationship between X and y ;

ε = n x 1 disturbance matrix;

k = number of RHS variables; and

n = number of observations.

For the ith observation (i.e. one row of X and y), the disturbance is:

Eq. **3.2**

$$\varepsilon_i = y_i - x_i\beta \qquad \mathbf{4.2}$$

If b is a column vector of estimates for β , then the residual of the ith data point, e_i , is used as an estimate for ε_i and is calculated by:

Eq. **3.3**

$$e_i = y_i - x_i b \qquad \mathbf{4.3}$$

The OLS estimator computes the vector b that minimizes the sum of squared residuals over all data points; i.e.

Eq. **3.4**

$$\text{Minimize: } \sum_{i=1}^{n} e_{i0}^2 = \sum_{i=1}^{n} \left(y_i - x_i b_0\right)^2 \qquad \mathbf{4.4}$$

If the inverse of $X'X$ exists, then the solution is:

Eq. **4.5**

$$b = \left(X'X\right)^{-1} X'y \qquad \mathbf{4.5}$$

OLS represents the practical approach of fitting a regression line to data as closely as possible. Under a set of six assumptions, the Gauss-Markov theorem states that OLS is the BLUE [**60**]. These assumptions are covered by most econometrics textbooks (e.g. [**59**], [**60**]). Table **4-1** provides a brief description of each assumption and the impacts of violations on parameter estimates.

Table **4-1**

Table **4-1**: Assumptions under which OLS is the BLUE

Assumption	Description	Impact of Violation(s)
Linearity	The dependent variable is an unchanging linear function of the known independent variables and a disturbance. Possible violations of the linearity assumption are an incorrect set of independent variables, non-linearity and changing parameter values.	Biased/inconsistent parameters Inefficient parameters
$E[\varepsilon_i \mid X] = 0$	The disturbance has a conditional expected value of zero for every observation. The independent variables do not carry useful information for the prediction of ε_i. This assumption is related to the exogeneity assumption.	Biased intercept
Full rank	There is no exact linear relationship among any of the independent variables in the model.	Model cannot be estimated Inefficient parameters (for less severe case of multicollinearity)
Spherical disturbances	The disturbance has constant variance no matter what the value of regressor variables (i.e. $Var[\varepsilon_i \mid X] = \sigma^2$) and the disturbances across all observations are uncorrelated (i.e. $Cov[\varepsilon_i, \varepsilon_j \mid X] = 0$).	Inefficient parameters
Exogeneity	The data generating mechanism of X is unrelated to ε whether X consists of constants, random variables or a mixture of both.	Biased/inconsistent parameters
$\varepsilon \mid X \sim N[0, \sigma^2 I]$	The disturbances are normally distributed.	Biased/inconsistent parameters (in small samples)

4.2 Model Specification and Estimation with OLS

The mechanisms influencing speed in work zones are poorly understood. A number of conceptual driver behavior based models have been proposed which identify elements of the roadway environment as influential factors of driver speed (e.g., [**62**], [**63**]). However, theoretical details to guide the specification of Eq. **3.1** through Eq. **3.4**, including functional form and RHS variables, do not exist. General specification principles were discussed in **3.6**. Additional details are summarized here.

Consistent with work by Shankar and Mannering [**54**], the logarithms of 85th percentile speeds and speed deviations were used for estimation. A log-linear functional form maintains two desirable properties: non-negativity of speed measures and monotonic relationship between LHS and RHS variables (i.e. no large "jump" in the LHS variables with a small change in RHS variables). As an example, the functional form of the model for 85th percentile passenger car speed (Eq. **3.1**) is:

Eq. **4.6**

$$\ln s_c = \alpha_{sc} + X_{sc}\beta_{sc} + Z_{sc}\gamma_{sc} + \varepsilon_{sc} \qquad \textbf{4.6}$$

Taking the exponential of both sides of Eq. **4.6** gives:

Eq. **4.7**

$$s_c = \exp(\alpha_{sc} + X_{sc}\beta_{sc} + Z_{sc}\gamma_{sc} + \varepsilon_{sc}) = e^{\alpha_{sc}} e^{X_{sc}\beta_{sc}} e^{Z_{sc}\gamma_{sc}} e^{\varepsilon_{sc}} \qquad \textbf{4.7}$$

The model structure for 85th percentile speed is multiplicative, including the error term ($e^{\varepsilon_{sc}}$) which has an expected value of one. The parameters and other model statistics (e.g., R-squared) estimated by OLS are applicable to the logarithm of 85th percentile speed. Transformations to the multiplicative form are needed to interpret relationships between RHS variables and 85th percentile speed.

A general-to-specific specification strategy was used in a sense that all variables related to traffic control, roadway and roadside infrastructure and other work zone features may possibly be associated with speed magnitudes and deviations. General categories for exogenous RHS variables are summarized in Table **3-4** and Table **3-5**. Variables representing different elements of the work zone environment took several forms as continuous and/or dummy variables. A summary of the variable forms that were tested is provided in Table **4-2**. Continuous variable forms usually consisted of actual dimensional values (e.g. traveled way width in units of feet). Dummy variable forms were categorical (e.g. a binary variable indicating whether traveled way width is greater than 12 feet).

A series of preliminary estimation runs repeatedly yielded the following observations:

- No measure of horizontal curvature was associated with speed magnitude.
- Posted speed as an indicator variable was superior to its continuous form.
- Posted speed was associated with speed magnitude where change in posted speed from upstream of the work zone to in the work zone was associated with speed deviation.
- Sample size limitations influenced specifications of two variables:
    - Presence of crest vertical curvature could not be specified separately; it was combined with presence of positive grades.
    - The effects of barrier offsets could not be determined; the variable was instead specified as barrier presence (at all offsets less than 12 feet).
- Total paved width had the strongest association of all roadway cross section variables with speed magnitude and deviation.
- Upstream (of the work zone) measures of speed were not associated with speed behavior in the work zone.

These observations contributed to developing general specifications for Eq. **3.1** through Eq. **3.4** that were estimated using four different data sets:

- Horizontal curves in the work area;
- Horizontal tangents in the work area;
- All data in the work area; and
- All data combined.

Only exogenous RHS variables were included in the general specifications (i.e. $\gamma_{sc} = \gamma_{st} = \gamma_{dc} = \gamma_{dt} = 0$ in Eq. **3.1** through Eq. **3.4**). With this restriction, the model structure had the following general form (with variable notations previously defined):

Eq. **4.8**

$$\ln s_c = \alpha_{sc} + X_{sc}\beta_{sc} + \varepsilon_{sc} \qquad \textbf{4.8}$$

Eq. **4.9**

$$\ln s_t = \alpha_{st} + X_{st}\beta_{st} + \varepsilon_{st} \qquad \textbf{4.9}$$

Eq. **4.10**

$$\ln d_c = \alpha_{dc} + X_{dc}\beta_{dc} + \varepsilon_{dc} \qquad \textbf{4.10}$$

Eq. **4.11**

$$\ln d_t = \alpha_{dt} + X_{dt}\beta_{dt} + \varepsilon_{dt} \qquad \textbf{4.11}$$

Estimation results for the general specifications using these four data sets are summarized in Table **4-3** through Table **4-6**. The tables show the RHS variables in the general specifications as well as the estimated parameter magnitudes and signs for each data set. In addition, a summary indicating different levels of parameter stability related to sign consistency and statistical significance is provided. Parameter stability related to statistical significance was observed by noting the number of times the probability of a type I error was less than 33 percent across the four estimations. This value was considered an appropriate balance between inflated standard errors due to irrelevant variables and type II errors in subsequent specifications.

Table **4-2**

Table **4-2**: Continuous and dummy variables tested

Category of RHS variables	**Continuous forms tested**	**Dummy forms tested**
Work zone strategy	None	Work zone type (lane closure or median crossover) Left or right lane closure Interaction of work zone type with left or right lane closure
Posted speed	Posted speed	Posted speed Difference between upstream and work zone posted speeds
Roadway type	None	Temporary or permanent
Horizontal alignment	Inverse of radius Degree of curve Squares and cubes of inverse radius and degree of curve	Curve presence Curve direction Level of curve degree (i.e. sharpness)
Vertical alignment	Grade Rate of curvature (if on curve) Inverse of rate of curvature (if on curve)	Type of alignment (i.e. upgrade, downgrade, crest, sag) Vertical curve presence
Work zone related traffic control devices	None	Presence and offset of concrete barrier on left or right side of traveled way Presence of "soft" devices (e.g. vertical panel, drum) on left or right side of traveled way No devices (i.e. normal roadside) on left or right side of traveled way
Location in work zone	Downstream distance from lane taper	Downstream distance from lane taper Location (lane taper or work area)
Cross Section	Traveled way width Right shoulder width Left shoulder width Total paved width	Total paved width
Traffic characteristics	Proportion of trucks in sample Upstream speed characteristics Logarithm of 85th percentile speed Logarithm of speed deviation	None

Table **4-3**

Table **4-3**: Parameter estimation and stability for models of logarithm of 85th percentile passenger car speed

	1	2	3	4	+	-	$p \leq 0.33$
Constant	4.0024	4.0129	4.0483	4.0362	4	0	4
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0832	-0.0886	-0.1092	-0.0844	0	4	4
Indicator of lane closed (1 if left lane closure; 0 if right lane)	0.0085	-0.0086	0.0136	-0.0027	2	2	0
Downstream distance from lane taper (mile)	-0.0072	-0.0078	-0.0061	-0.0053	0	4	4
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1304	0.1181	0.1259	0.1205	4	0	4
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0982	0.1177	0.1087	0.0969	4	0	4
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1513	0.1169	0.1301	0.1449	4	0	4
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0564	0.0689	0.0500	0.0428	4	0	4
Inverse of horizontal curve radius (1/ft x 1000)	-0.0123		0.0095	-0.0109	1	2	1
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0241	-0.00152	-0.0199	-0.0258	0	4	3
Total paved width (ft)	0.0038	0.0028	0.0018	0.0022	4	0	4
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0364	-0.0215	-0.0400	-0.0347	0	4	3
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	0.0021	-0.0213	0.0029	0.0088	3	1	0
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	0.0026	-0.0064	-0.0068	-0.0089	1	3	0
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	0.0064	-0.0053	0.0042	0.0095	3	1	0
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)				0.0575	1	0	1

1: horizontal curves in work area (n = 44)
2: horizontal tangents in work area (n = 52)
3: all data in work area (n = 96)
4: all data (n = 119)
+: number of times parameter is positive
-: number of times parameter is negative
$p \leq 0.33$: number of times p-value (i.e. the probability of falsely rejecting the null hypothesis that the regression parameter equals zero) is less than or equal to 33 percent

Table **4-4**

Table **4-4**: Parameter estimation and stability for models of logarithm of 85th percentile truck speed

	1	2	3	4	+	-	$p \leq 0.33$
Constant	4.0370	3.9840	4.0085	3.9881	4	0	4
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0525	-0.1009	-0.1104	-0.0833	0	4	4
Indicator of lane closed (1 if left lane closure; 0 if right lane)	-0.1083	-0.0085	-0.0026	-0.0155	0	4	1
Downstream distance from lane taper (mile)	-0.0036	-0.0060	-0.0034	-0.0025	0	4	3
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1093	0.1042	0.1029	0.0962	4	0	4
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0478	0.1255	0.1124	0.1006	4	0	4
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1252	0.0962	0.1150	0.1264	4	0	4
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0521	0.0738	0.0585	0.0516	4	0	4
Inverse of horizontal curve radius (1/ft x 1000)	-0.0727		-0.0116	-0.0271	0	3	2
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0240	-0.0176	-0.0278	-0.0320	0	4	3
Total paved width (ft)	0.0027	0.0026	0.0019	0.0026	4	0	4
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0514	-0.0075	-0.0202	-0.0163	0	4	1
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	0.0498	-0.0151	0.0050	0.0110	3	1	1
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0518	0.0129	0.0057	0.0017	3	1	1
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	0.0086	-0.0033	0.0047	0.0109	3	1	0
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)				0.0367	1	0	1
1: horizontal curves in work area (n = 44) 2: horizontal tangents in work area (n = 52) 3: all data in work area (n = 96) 4: all data (n = 119) +: number of times parameter is positive -: number of times parameter is negative $p \leq 0.33$: number of times p-value (i.e. the probability of falsely rejecting the null hypothesis that the regression parameter equals zero) is less than or equal to 33 percent							

Table **4-5**

Table **4-5**: Parameter estimation and stability for models of logarithm of passenger car speed deviation

	1	2	3	4	+	-	$p \leq 0.33$
Constant	2.0538	1.9918	1.9873	1.9815	4	0	4
Indicator of work zone type (1 if lane closure; 0 if median crossover)	0.0786	-0.0373	-0.0172	-0.0427	1	3	0
Indicator of lane closed (1 if left lane closure; 0 if right lane)	-0.1502	0.0487	0.0404	0.0380	3	1	0
Downstream distance from lane taper (mile)	-0.0197	-0.0325	-0.0241	-0.0253	0	4	4
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1025	-0.1334	-0.1086	-0.0953	0	4	4
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1045	0.0395	-0.0395	-0.0286	1	3	1
Inverse of horizontal curve radius (1/ft x 1000)	-0.1107		-0.0472	-0.0826	0	3	1
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0065	0.0038	-0.0073	0.0072	2	2	0
Total paved width (ft)	-0.0071	-0.0044	-0.0059	-0.0058	0	4	3
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1914	-0.0820	-0.1153	-0.1164	0	4	4
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0936	-0.1538	-0.0885	-0.0795	0	4	4
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.1163	-0.1453	-0.0840	-0.0745	0	4	3
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0259	-0.1830	-0.1025	-0.1100	0	4	3
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)				0.0268	1	0	0

1: horizontal curves in work area (n = 44)
2: horizontal tangents in work area (n = 52)
3: all data in work area (n = 96)
4: all data (n = 119)
+: number of times parameter is positive
-: number of times parameter is negative
$p \leq 0.33$: number of times p-value (i.e. the probability of falsely rejecting the null hypothesis that the regression parameter equals zero) is less than or equal to 33 percent

Table **4-6**

Table **4-6**: Parameter estimation and stability for models of logarithm of truck speed deviation

	1	2	3	4	+	-	$p \leq 0.33$
Constant	1.9061	2.0067	1.9291	1.8993	4	0	4
Indicator of work zone type (1 if lane closure; 0 if median crossover)	0.2842	-0.0947	0.0909	0.0537	3	1	2
Indicator of lane closed (1 if left lane closure; 0 if right lane)	-0.2873	0.0514	-0.0767	-0.0264	1	3	1
Downstream distance from lane taper (mile)	-0.0111	-0.0370	-0.0245	-0.0233	0	4	4
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1327	-0.1676	-0.1570	-0.1599	0	4	4
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.2426	-0.0881	-0.1660	-0.1612	0	4	4
Inverse of horizontal curve radius (1/ft x 1000)	-0.2985		-0.2594	-0.3143	0	3	4
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	0.0726	0.0361	0.0358	0.0393	4	0	2
Total paved width (ft)	-0.0086	-0.0089	-0.0088	-0.0074	0	4	4
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0601	-0.0874	-0.0254	-0.0428	0	4	1
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0604	-0.0315	-0.0437	0.0098	1	3	0
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.1398	0.0181	-0.0287	-0.0239	1	3	1
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0078	-0.1124	-0.0540	-0.0394	0	4	2
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)				0.0582	1	0	1

1: horizontal curves in work area (n = 44)
2: horizontal tangents in work area (n = 52)
3: all data in work area (n = 96)
4: all data (n = 119)
+: number of times parameter is positive
-: number of times parameter is negative
$p \leq 0.33$: number of times p-value (i.e. the probability of falsely rejecting the null hypothesis that the regression parameter equals zero) is less than or equal to 33 percent

Variables that exhibited fairly constant parameter signs and levels of statistical significance in Table **4-3** through Table **4-6** were included in more concise specifications of Eq. **4.8** through Eq. **4.11**. OLS estimations of these concise specifications used the entire data set of 119 observations. The results are summarized in Table **4-7** through Table **4-10**. The tables report estimated regression coefficients (b) and their standard errors (S.E. $\{b\}$), t-statistics (t), probabilities (*p-value*) of a type I error (where the null hypothesis is that $b = 0$) and means of the RHS variables ($\overline{X}$). Variables were included in the reported specifications if the probability of a type I error was less than 33 percent. The following model statistics are also provided:

- Residual Sum of Squared Errors (*SSE*);
- R-squared (R^2);
- Adjusted R-squared (R^2_{adj}); and
- Durbin-Watson statistic for first order serial correlation (*DW*).

The number of observations used for model estimation (*N*) is also provided. Model parameters are discussed in detail in **4.5**.

Table **4-7**

Table **4-7**: OLS estimates for logarithm of 85th percentile passenger car speed

	b	S.E. {*b*}.	*t*	*p-value*	$\overline{X}$
Constant	4.0237	0.0310	129.86	0.0000	
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0829	0.0199	-4.16	0.0001	0.43
Downstream distance from lane taper (mile)	-0.0049	0.0027	-1.82	0.0709	2.46
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1163	0.0184	6.32	0.0000	0.29
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0948	0.0183	5.18	0.0000	0.19
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1401	0.0168	8.35	0.0000	0.18
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0465	0.0166	2.80	0.0060	0.75
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0292	0.0134	-2.18	0.0315	0.29
Total paved width (ft)	0.0027	0.0012	2.21	0.0292	19.89
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0274	0.0172	-1.60	0.1132	0.39
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0547	0.0176	3.10	0.0025	0.19
N = 119; SSE = 0.3863; R^2 = 0.622; R^2_{adj} = 0.587; DW = 1.75					

Table **4-8**

Table **4-8**: OLS estimates for logarithm of 85th percentile truck speed

	b	S.E. {*b*}.	*t*	*p-value*	$\overline{X}$
Constant	3.9867	0.0287	138.83	0.0000	
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0900	0.0185	-4.85	0.0000	0.43
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0916	0.0159	5.75	0.0000	0.29
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.1031	0.0170	6.06	0.0000	0.19
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1297	0.0156	8.33	0.0000	0.18
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0584	0.0153	3.81	0.0002	0.75
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0351	0.0123	-2.86	0.0051	0.29
Total paved width (ft)	0.0026	0.0011	2.29	0.0238	19.89
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0235	0.0148	-1.58	0.1161	0.39
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0379	0.0159	2.39	0.0187	0.19
$N = 119$; $SSE = 0.3372$; $R^2 = 0.616$; $R^2_{adj} = 0.585$; $DW = 1.61$					

Table **4-9**

Table **4-9**: OLS estimates for logarithm of passenger car speed deviation

	b	S.E. {*b*}.	*t*	*p-value*	$\overline{X}$
Constant	1.8969	0.0689	27.53	0.0000	
Downstream distance from lane taper (mile)	-0.0259	0.0056	-4.64	0.0000	2.46
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.0720	0.0286	-2.52	0.0132	0.58
Total paved width (ft)	-0.0035	0.0026	-1.32	0.1893	19.89
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1203	0.0406	-2.96	0.0037	0.39
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0918	0.0352	-2.61	0.0104	0.19
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0892	0.0398	-2.24	0.0270	0.39
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.1121	0.0341	-3.29	0.0014	0.36
N = 119; SSE = 2.088; R^2 = 0.512; R^2_{adj} = 0.481; DW = 1.62					

Table **4-10**

Table **4-10**: OLS estimates for logarithm of truck speed deviation

	b	S.E. {*b*}.	*t*	*p-value*	$\overline{X}$
Constant	1.9276	0.0923	20.88	0.0000	
Downstream distance from lane taper (mile)	-0.0231	0.0068	-3.38	0.0010	2.46
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1822	0.0343	-5.31	0.0000	0.58
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1447	0.0424	-3.41	0.0009	0.75
Inverse of horizontal curve radius (1/ft x 1000)	-0.3049	0.1113	-2.74	0.0072	0.10
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	0.0330	0.0352	0.94	0.3501	0.29
Total paved width (ft)	-0.0079	0.0035	-2.24	0.0269	19.89
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0504	0.0420	-1.20	0.2329	0.39
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0389	0.0351	-1.11	0.2701	0.39
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0539	0.0466	1.16	0.2497	0.19
N = 119; SSE = 2.840; R^2 = 0.511; R^2_{adj} = 0.470; DW = 1.89					

4.3 Seemingly Unrelated Regression Estimation

The parameters in Table **4-7** through Table **4-10** are estimated one equation at a time when OLS is used. Depending on the data generating processes, specifically the disturbances for each equation, the OLS estimator is consistent but may not be efficient. The random disturbance terms, ε_{sc} , ε_{st} , ε_{dc} and ε_{dt} (see Eq. **4.8** through Eq. **4.11**) are present for several reasons, one of which being that every influence on the dependent variable of interest cannot be observed. The omitted factors with a random influence on the dependent variable are captured in the disturbance. Measurement errors in the dependent variable are another contributor to the disturbance.

There may be a group of similar factors contemporaneously affecting the disturbances for 85th passenger car speed, 85th percentile truck speed, and respective speed deviations. Estimating the model as a system may result in efficiency gains. In the model formulation below, only exogenous RHS variables are included and the equations are linked only through there disturbance. This technique, referred to as seemingly unrelated regression (SUR), was introduced by Zellner [**64**].

In SUR, Eq. **4.8** through Eq. **4.11** are written as a stacked model:

Eq. **4.12**

$$\begin{bmatrix} s_c \\ s_t \\ d_c \\ d_t \end{bmatrix} = \begin{bmatrix} X_{sc} & 0 & 0 & 0 \\ 0 & X_{st} & 0 & 0 \\ 0 & 0 & X_{dc} & 0 \\ 0 & 0 & 0 & X_{dt} \end{bmatrix} \begin{bmatrix} \beta_{sc} \\ \beta_{st} \\ \beta_{dc} \\ \beta_{dt} \end{bmatrix} + \begin{bmatrix} \varepsilon_{sc} \\ \varepsilon_{st} \\ \varepsilon_{dc} \\ \varepsilon_{dt} \end{bmatrix} = X_* \beta_* + \varepsilon_* \qquad \mathbf{4.12}$$

For each individual observation, the variance-covariance matrix of the disturbances is:

Eq. **4.13**

$$\Sigma = \begin{bmatrix} \sigma_{scsc} & \sigma_{scst} & \sigma_{scdc} & \sigma_{scdt} \\ \sigma_{stsc} & \sigma_{stst} & \sigma_{stdc} & \sigma_{stdt} \\ \sigma_{dcsc} & \sigma_{dcst} & \sigma_{dcdc} & \sigma_{dcdt} \\ \sigma_{dtsc} & \sigma_{dtst} & \sigma_{dtdc} & \sigma_{dtdt} \end{bmatrix} \qquad \mathbf{4.13} \quad .$$

Therefore, the variance-covariance matrix of the entire stacked model with *n* observations is (in this case) the *4n* x *4n* matrix:

Eq. **4.14**

$$\Omega = \Sigma \otimes I = E\left\lfloor \varepsilon_* \varepsilon_*^{'} \mid X_{sc} X_{st} X_{dc} X_{dt} \right\rfloor \qquad \mathbf{4.14}$$

where I is an *n* x *n* identity matrix. The generalized least squares (GLS) estimate of β_* is:

Eq. **4.15**

$$b_* = \left(X'\Omega^{-1}X\right)^{-1} X'\Omega^{-1}y \qquad \textbf{4.15}$$

Using the residuals from equation-by-equation OLS provides consistent estimates of the elements of Σ. Estimation of SUR models is a full-information technique (i.e. it uses information available in the entire system as opposed to only information in each equation) and it offers efficiency gains over OLS under two conditions [**60**]:

- The equations are actually related through their disturbance (i.e. Σ has off-diagonal elements that are non-zero); and
- The equations do not have identical explanatory variables.

If the equations are not related, then full-information GLS is the same as equation-by-equation OLS. In general, the greater the correlation in the disturbances and the smaller the correlation in explanatory variable matrices, the greater the efficiency gains with SUR.

Breusch and Pagan suggested a Lagrange multiplier (LM) test to determine whether the variance-covariance matrix is diagonal [**65**]. The steps of the test were summarized in [**57**] and [**60**]:

1. Use equation-by-equation OLS and the resulting residuals to estimate the elements of Σ.
2. Calculate the LM statistic:

Eq. **4.16**

$$\lambda_{LM} = T\sum_{i=2}^{M}\sum_{j=1}^{i-1} r_{ij}^2 \qquad \textbf{4.16}$$

where: r_{ij} = the estimated correlation between the disturbance of equations *i* and equation *j*;

M = number of equations in the system; and

T = total number of observations.

The LM statistic is chi-square distributed with $M(M-1)/2$ degrees of freedom. The null hypothesis of the test is that $\sigma_{ij} = 0$ for all $i \neq j$.

The estimates of the elements of Σ using the OLS specifications in Table **4-7** through Table **4-10** were:

Eq. **4.17**

$$\hat{\Sigma} = \begin{bmatrix} 0.00327 & 0.00275 & -0.00033 & -0.00136 \\ 0.00275 & 0.00286 & -0.00024 & -0.00023 \\ -0.00033 & -0.00024 & 0.01769 & 0.00956 \\ -0.00136 & -0.00023 & 0.00956 & 0.02406 \end{bmatrix} \qquad \mathbf{4.17}$$

The hypothesis, result and conclusion of the LM test using the estimates in Eq. **4.17** to determine all values of r_{ij} is summarized in Figure **4-1**.

Figure **4-1**

H$_0$: $\sigma_{ij} = 0$ for all $i \neq j$

Test: $\lambda_{LM} = 125 > \chi_{(d.f.=6;\alpha=0.01)} = 16.81$

Conclusion: With the probability of a type I error equal to 1 percent, the null hypothesis that the variance-covariance matrix Σ is diagonal is rejected

Figure **4-1**: Hypothesis, result and conclusion of Breusch and Pagan LM test

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The results of the Breusch and Pagan LM test indicated efficiency gains would result from SUR. The results of the SUR estimations as well as comparisons to OLS-estimated parameter magnitudes and standard errors are provided in Table **4-11** through Table **4-14**. The SSE decreased by a minimum of 6.6 percent and a maximum of 8.7 percent for the SUR models. In addition, standard errors of parameter estimates decreased by anywhere from 3 to 59 percent, with an average 9 percent decrease. Most parameter estimates stayed fairly stable between OLS and SUR (22 of 39 estimates changed by less than 3 percent).

Table **4-11**

Table **4-11**: SUR estimates for logarithm of 85th percentile passenger car speed

	b_{SURE}	$S.E..(b_{SURE})$	b_{OLS}	$S.E.(b_{OLS})$
Constant	4.0225	0.0295	4.0237	0.0310
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0808	0.0188	-0.0829	0.0199
Downstream distance from lane taper (mile)	-0.0029	0.0011	-0.0049	0.0027
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1084	0.0164	0.1163	0.0184
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0904	0.0173	0.0948	0.0183
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1381	0.0159	0.1401	0.0168
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0471	0.0157	0.0465	0.0166
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0310	0.0126	-0.0292	0.0134
Total paved width (ft)	0.0027	0.0012	0.0027	0.0012
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0303	0.0154	-0.0274	0.0172
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0586	0.0164	0.0547	0.0176
SUR: N = 119; SSE = 0.3527; R^2 = 0.620; R^2_{adj} = 0.584; DW = 1.75				

Table **4-12**

Table **4-12**: SUR estimates for logarithm of 85th percentile truck speed

	b_{SURE}	$S.E..(b_{SURE})$	b_{OLS}	$S.E.(b_{OLS})$
Constant	3.9870	0.0275	3.9867	0.0287
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0897	0.0177	-0.0900	0.0185
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0917	0.0152	0.0916	0.0159
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.1023	0.0163	0.1031	0.0170
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1304	0.0149	0.1297	0.0156
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0582	0.0147	0.0584	0.0153
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0348	0.0117	-0.0351	0.0123
Total paved width (ft)	0.0026	0.0011	0.0026	0.0011
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0236	0.0142	-0.0235	0.0148
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0381	0.0152	0.0379	0.0159
SUR: N = 119; SSE = 0.3089; R^2 = 0.616; R^2_{adj} = 0.585; DW = 1.61				

Table **4-13**

Table **4-13**: SUR estimates for logarithm of passenger car speed deviation

	b_{SURE}	$S.E..(b_{SURE})$	b_{OLS}	$S.E.(b_{OLS})$
Constant	1.8832	0.0636	1.8969	0.0689
Downstream distance from lane taper (mile)	-0.0262	0.0054	-0.0259	0.0056
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.0720	0.0275	-0.0720	0.0286
Total paved width (ft)	-0.0033	0.0025	-0.0035	0.0026
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1108	0.0379	-0.1203	0.0406
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0934	0.0298	-0.0918	0.0352
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0731	0.0340	-0.0892	0.0398
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.1054	0.0319	-0.1121	0.0341
SUR: N = 119; SSE = 1.950; R^2 = 0.511; R^2_{adj} = 0.480; DW = 1.61				

Table **4-14**

Table **4-14**: SUR estimates for logarithm of truck speed deviation

	b_{SURE}	$S.E..(b_{SURE})$	b_{OLS}	$S.E.(b_{OLS})$
Constant	1.8999	0.0825	1.9276	0.0923
Downstream distance from lane taper (mile)	-0.0231	0.0065	-0.0231	0.0068
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1824	0.0323	-0.1822	0.0343
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1266	0.0357	-0.1447	0.0424
Inverse of horizontal curve radius (1/ft x 1000)	-0.2433	0.0888	-0.3049	0.1113
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	0.0278	0.0298	0.0330	0.0352
Total paved width (ft)	-0.0074	0.0033	-0.0079	0.0035
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0561	0.0398	-0.0504	0.0420
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0301	0.0318	-0.0389	0.0351
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0424	0.0396	0.0539	0.0466
SUR: N = 119; SSE = 2.613; R^2 = 0.508; R^2_{adj} = 0.468; DW = 1.87				

4.4 Investigation of Autocorrelation in OLS and SUR Models

The estimated Durbin-Watson test-statistics from OLS and SUR (less than 2.0 in all cases), as well as the nature of how the data were collected (i.e., several locations in each work zone) prompted investigation of potential autocorrelation issues. Autocorrelation is a violation of the spherical disturbance assumption of OLS (i.e. violation of $Cov[\varepsilon_i, \varepsilon_j \mid X] = 0$ in Table **4-1**) and is common in time series data. Depending on the interpretation of "time," the data described in Chapter 3 may be viewed as purely cross-sectional or pooled cross-section and time series data. Autocorrelation results in inefficient OLS estimates or underestimated values for standard errors and inflated R-squared values in the case of positive autocorrelation. It is a complex phenomenon that will not receive full attention in this research. This section will present the results of commonly used methods to address its existence as well as "corrected" GLS estimates.

When autocorrelation is present, the disturbance in time period (*t-1*) contains information regarding the disturbance in time period (*t*). Two general types of autocorrelation, positive and negative, exist. A positive (or negative) disturbance is likely to be followed by another positive (or negative) disturbance when there is positive autocorrelation. A positive or negative disturbance is likely to be followed by a disturbance of the opposite sign when there is negative autocorrelation. The disturbance is estimated using OLS residuals. Residual plots for the OLS models are shown in Figure **4-2** through Figure **4-5**. The sinuous appearance of the residual plots (more apparent in Figure **4-2** and Figure **4-3** than in Figure **4-4** and Figure **4-5**) as well as the Durbin-Watson values from OLS and SUR with values less than 2 indicate positive autocorrelation. An important caveat is that the Durbin-Watson statistic tests only for first-order autocorrelation (see Eq. **4.18**, Eq. **4.19** and Eq. **4.20**). The residual plots indicate potential autocorrelation of a higher order. Only first-order models are considered in this research.

The first-order autoregressive (AR1) model is the simplest and most widely used technique to address autocorrelation. Greene explained [**60**]:

> "Processes more involved than this model are usually extremely difficult to analyze…[and] It is very optimistic to expect to know precisely the correct form …for the disturbance in any given situation. The first-order autoregression has withstood the test of time and experimentation as a reasonable model for underlying processes that probably, in truth, are impenetrably complex."

Figure **4-2**

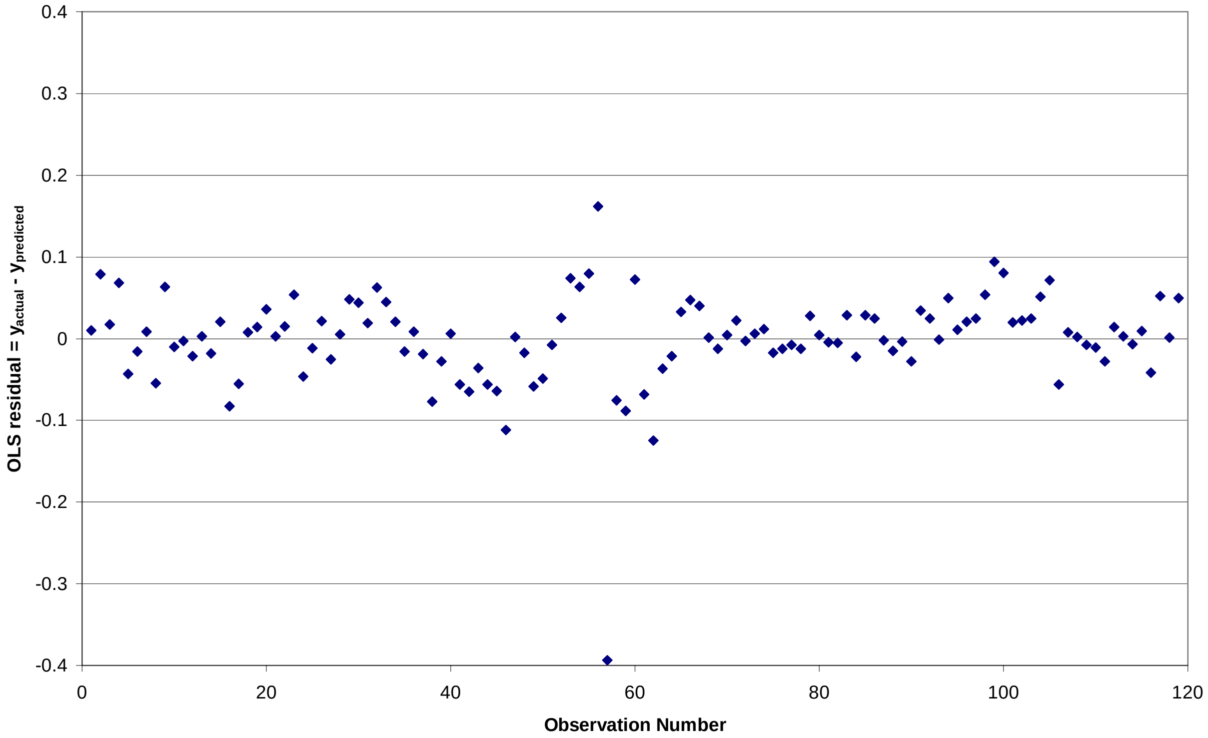

Figure **4-2**: OLS residuals for logarithm of 85th percentile passenger car speed

Figure **4-3**

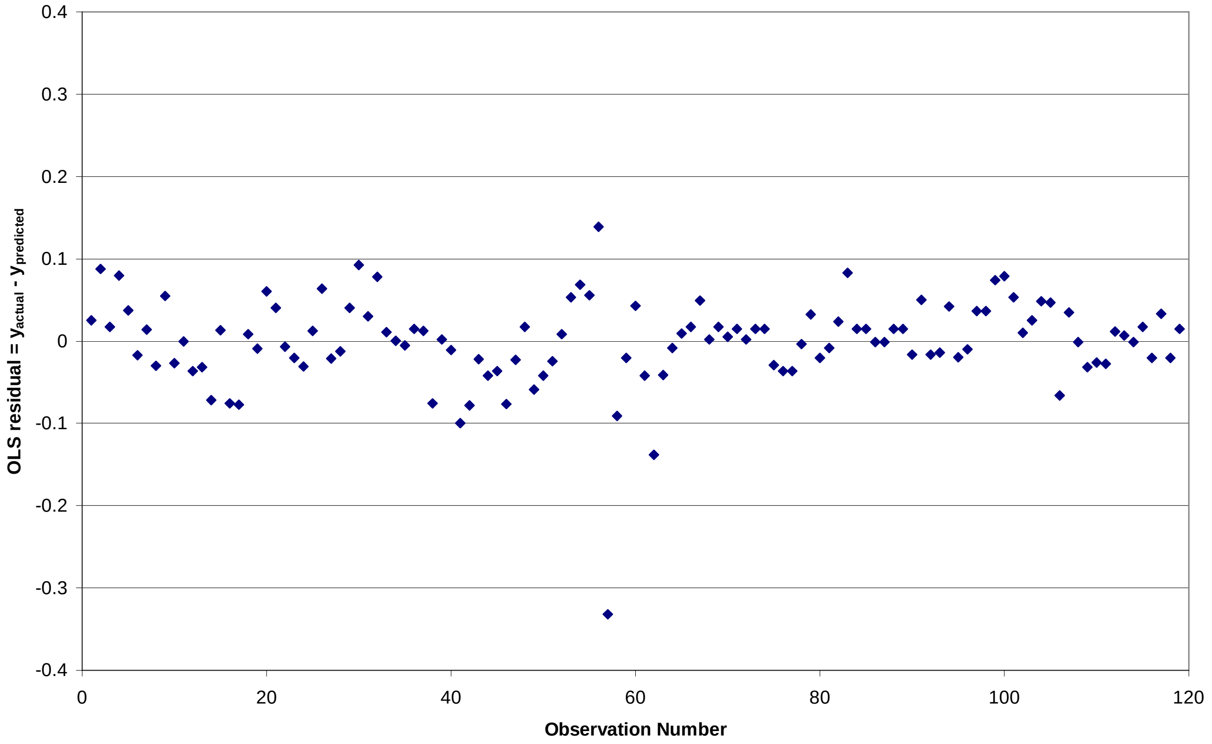

Figure **4-3**: OLS residuals for logarithm of 85th percentile truck speed

Figure **4-4**

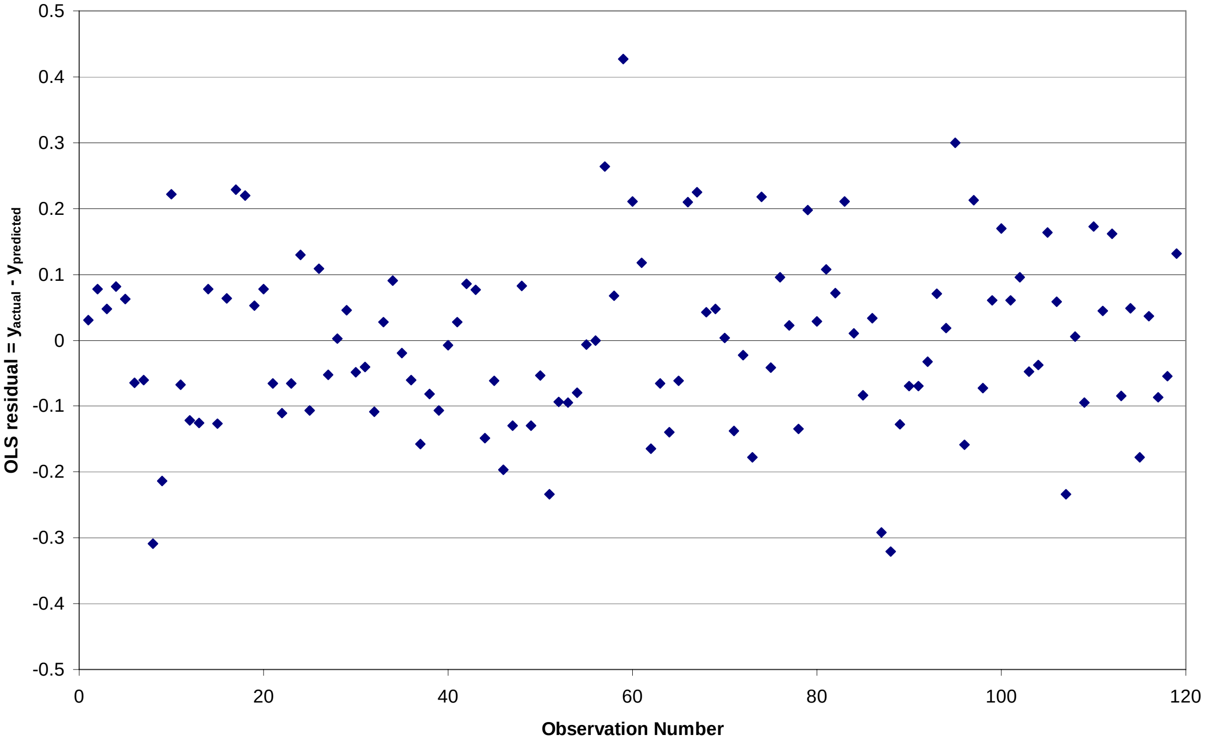

Figure **4-4**: OLS residuals for logarithm of passenger car speed deviation

Figure **4-5**

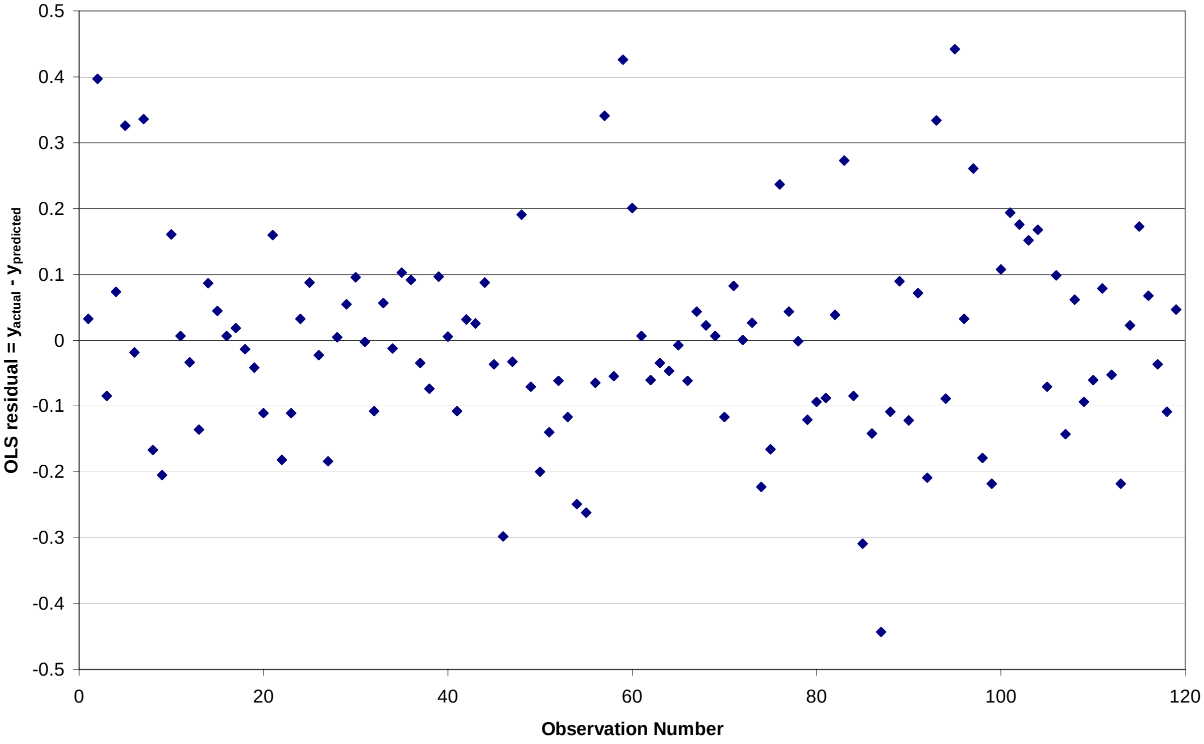

Figure **4-5**: OLS residuals for logarithm of truck speed deviation

The AR1 model takes the form

Eq. **4.18**

$$Y_t = \alpha + \beta X_t + \varepsilon_t = \alpha + \beta X_t + \rho \varepsilon_{t-1} + u_t \qquad \textbf{4.18}$$

The disturbance (ε_t) is related to the disturbance in the previous time period (ε_{t-1}) through the first-order autocorrelation coefficient (ρ), which takes a value between -1 and 1. The term u_t takes the properties of the traditional disturbance: $E[u_t] = 0$, $E[u_t^2] = \sigma_u^2$ and $Cov[u_t, u_s] = 0$ for all $t \neq s$. The Prais and Winsten GLS estimator was used to estimate the parameters for the AR1 models [**66**]. This consists of the following computational steps:

1. Regression Y_t on X_t using OLS.
2. Estimate the disturbance (ε_t) with the OLS residuals (e_t).
3. Calculate the Durbin-Watson test statistic:

Eq. **4.19**

$$d = \frac{\sum_{t=2}^{T} (e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2} \qquad \textbf{4.19}$$

4. Estimate the autocorrelation coefficient (ρ) with:

Eq. **4.20**

$$r = 1 - (0.5 * d) \qquad \textbf{4.20}$$

5. Regress Y_t^* on X_t^* using OLS where:

Eq. **4.21**

$$Y_t^* = \begin{bmatrix} \sqrt{1-r^2}\,y_1 \\ y_2 - ry_1 \\ y_3 - ry_2 \\ . \\ . \\ . \\ y_T - ry_{T-1} \end{bmatrix}, \; X_t^* = \begin{bmatrix} \sqrt{1-r^2}\,x_1 \\ x_2 - rx_1 \\ x_3 - rx_2 \\ . \\ . \\ . \\ x_T - rx_{T-1} \end{bmatrix} \qquad \textbf{4.21}$$

Note: x_i = the ith row of previously defined matrix X

6. Iterate steps 2 through 5 until value for *r* converges.

AR1 estimation procedures are available for equation-by-equation OLS and SUR models. Results of first-order autoregressive models for OLS (AR1-OLS) and SUR (AR1-SUR) are summarized in Table **4-15** through Table **4-22**. The tables include the parameter estimates and standard errors for the AR1 models as well as those from the traditional OLS and SUR models. AR1 model statistics including the final estimate of the autocorrelation coefficient and an updated estimate of the Durbin-Watson statistic are also included. As expected with positive autocorrelation, standard errors in the AR1 models were on average 4 to 5 percent higher than the OLS and SUR models.

Table **4-15**

Table **4-15**: AR1-OLS estimates for logarithm of 85th percentile passenger car speed

	b_{OLS}^{AR1}	$S.E.\left(b_{OLS}^{AR1}\right)$	b_{OLS}	$S.E.\left(b_{OLS}\right)$
Constant	4.0386	0.0324	4.0237	0.0310
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0766	0.0218	-0.0829	0.0199
Downstream distance from lane taper (mile)	-0.0058	0.0031	-0.0049	0.0027
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1195	0.0214	0.1163	0.0184
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0908	0.0206	0.0948	0.0183
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1427	0.0196	0.1401	0.0168
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0411	0.0170	0.0465	0.0166
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0216	0.0131	-0.0292	0.0134
Total paved width (ft)	0.0020	0.0012	0.0027	0.0012
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0234	0.0178	-0.0274	0.0172
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0473	0.0177	0.0547	0.0176
RHO	0.1857	0.0905		
AR1: N = 119; DW = 2.06				

Table **4-16**

Table **4-16**: AR1-OLS estimates for logarithm of 85th percentile truck speed

	b_{OLS}^{AR1}	$S.E.\left(b_{OLS}^{AR1}\right)$	b_{OLS}	$S.E.(b_{OLS})$
Constant	4.0037	0.0301	3.9867	0.0287
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0796	0.0208	-0.0900	0.0185
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0929	0.0198	0.0916	0.0159
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0981	0.0199	0.1031	0.0170
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1319	0.0194	0.1297	0.0156
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0489	0.0156	0.0584	0.0153
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0262	0.0117	-0.0351	0.0123
Total paved width (ft)	0.0017	0.0011	0.0026	0.0011
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0177	0.0156	-0.0235	0.0148
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0335	0.0153	0.0379	0.0159
RHO	0.2628	0.0888		
AR1: N = 119; DW = 2.04				

Table **4-17**

Table **4-17**: AR1-OLS estimates for logarithm of passenger car speed deviation

	b_{OLS}^{AR1}	$S.E.\left(b_{OLS}^{AR1}\right)$	b_{OLS}	$S.E.(b_{OLS})$
Constant	1.8562	0.0701	1.8969	0.0689
Downstream distance from lane taper (mile)	-0.0267	0.0063	-0.0259	0.0056
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.0650	0.0337	-0.0720	0.0286
Total paved width (ft)	-0.0026	0.0026	-0.0035	0.0026
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1047	0.0425	-0.1203	0.0406
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0753	0.0360	-0.0918	0.0352
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0734	0.0402	-0.0892	0.0398
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0923	0.0343	-0.1121	0.0341
RHO	0.2175	0.0899		
AR1: N = 119; DW = 2.09				

Table **4-18**

Table **4-18**: AR1-OLS estimates for logarithm of truck speed deviation

	b_{OLS}^{AR1}	$S.E.\left(b_{OLS}^{AR1}\right)$	b_{OLS}	$S.E.(b_{OLS})$
Constant	1.9151	0.0927	1.9276	0.0923
Downstream distance from lane taper (mile)	-0.0233	0.0071	-0.0231	0.0068
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1813	0.0360	-0.1822	0.0343
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1378	0.0432	-0.1447	0.0424
Inverse of horizontal curve radius (1/ft x 1000)	-0.2986	0.1095	-0.3049	0.1113
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	0.0340	0.0351	0.0330	0.0352
Total paved width (ft)	-0.0076	0.0035	-0.0079	0.0035
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0456	0.0430	-0.0504	0.0420
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0409	0.0355	-0.0389	0.0351
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0496	0.0468	0.0539	0.0466
RHO	0.0634	0.0919		
AR1: N = 119; DW = 2.02				

Table **4-19**

Table **4-19**: AR1-SUR estimates for logarithm of 85th percentile passenger car speed

	b^{AR1}_{SURE}	$S.E.\left(b^{AR1}_{SURE}\right)$	b_{SURE}	$S.E..\left(b_{SURE}\right)$
Constant	4.0334	0.0300	4.0225	0.0295
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0743	0.0198	-0.0808	0.0188
Downstream distance from lane taper (mile)	-0.0030	0.0012	-0.0029	0.0011
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.1112	0.0180	0.1084	0.0164
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0853	0.0186	0.0904	0.0173
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1406	0.0175	0.1381	0.0159
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0406	0.0158	0.0471	0.0157
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0236	0.0124	-0.0310	0.0126
Total paved width (ft)	0.0021	0.0012	0.0027	0.0012
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0277	0.0159	-0.0303	0.0154
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0571	0.0162	0.0586	0.0164
RHO	0.1271			
AR1: *N* = 119; *DW* = 1.95				

Table **4-20**

Table **4-20**: AR1-SUR estimates for logarithm of 85th percentile truck speed

	b_{SURE}^{AR1}	$S.E.\left(b_{SURE}^{AR1}\right)$	b_{SURE}	$S.E..\left(b_{SURE}\right)$
Constant	4.0013	0.0281	3.9870	0.0275
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.0826	0.0191	-0.0897	0.0177
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0950	0.0177	0.0917	0.0152
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0988	0.0181	0.1023	0.0163
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.1327	0.0173	0.1304	0.0149
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0482	0.0147	0.0582	0.0147
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0277	0.0112	-0.0348	0.0117
Total paved width (ft)	0.0019	0.0011	0.0026	0.0011
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0204	0.0146	-0.0236	0.0142
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0388	0.0146	0.0381	0.0152
RHO	0.1957			
AR1: N = 119; DW = 1.92				

Table **4-21**

Table **4-21**: AR1-SUR estimates for logarithm of passenger car speed deviation

	b_{SURE}^{AR1}	$S.E.\left(b_{SURE}^{AR1}\right)$	b_{SURE}	$S.E..\left(b_{SURE}\right)$
Constant	1.8500	0.0648	1.8832	0.0636
Downstream distance from lane taper (mile)	-0.0266	0.0060	-0.0262	0.0054
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.0662	0.0316	-0.0720	0.0275
Total paved width (ft)	-0.0026	0.0025	-0.0033	0.0025
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1023	0.0396	-0.1108	0.0379
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0774	0.0306	-0.0934	0.0298
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0630	0.0345	-0.0731	0.0340
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0885	0.0320	-0.1054	0.0319
RHO	0.1902			
AR1: *N* = 119; *DW* = 2.01				

Table **4-22**

Table **4-22**: AR1-SUR estimates for logarithm of truck speed deviation

	b_{SURE}^{AR1}	$S.E.\left(b_{SURE}^{AR1}\right)$	b_{SURE}	$S.E..\left(b_{SURE}\right)$
Constant	1.8832	0.0834	1.8999	0.0825
Downstream distance from lane taper (mile)	-0.0233	0.0067	-0.0231	0.0065
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1802	0.0337	-0.1824	0.0323
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1220	0.0365	-0.1266	0.0357
Inverse of horizontal curve radius (1/ft x 1000)	-0.2370	0.0879	-0.2433	0.0888
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	0.0244	0.0300	0.0278	0.0298
Total paved width (ft)	-0.0068	0.0033	-0.0074	0.0033
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0529	0.0406	-0.0561	0.0398
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0278	0.0320	-0.0301	0.0318
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0425	0.0401	0.0424	0.0396
RHO	0.056			
AR1: N = 119; DW = 1.97				

4.5 Summary of Statistical Findings

This section summarizes the findings in **4.1** through **4.4**. Models in this chapter include only exogenous RHS variables; associations between speed measures (i.e. speed measures as RHS variables) were not considered. Considering exogenous-only specifications is consistent with most existing speed-modeling literature. A log-linear functional form was used because of two desirable properties: non-negativity of speed measures and monotonic relationship between LHS and RHS variables. The model structure had the following general form (with variable notations previously defined):

As with most empirical modeling work, OLS regression was a logical starting point for parameter estimation. However, results of the Breusch and Pagan LM test (see Figure **4-1**) on equation-by-equation OLS residuals indicated that disturbances across equations were correlated and efficiency gains would result from GLS estimation. The SUR estimator developed by Zellner was used [**64**]. The GLS estimator was more efficient than OLS. Respective model sums of squared errors decreased by approximately 7 to 9 percent. In addition, standard errors of parameter estimates decreased by anywhere from 3 to 59 percent, with an average 9 percent decrease.

Investigation of potential autocorrelation issues was prompted by the nature of the observational study (i.e., repeated measures in each work zone) as well as testing and observations of OLS residuals. Residual plots and Durbin-Watson test statistics indicated positive autocorrelation in the data. First-order autoregressive OLS and SUR models were estimated. As expected with positive autocorrelation, standard errors in the AR1 models were on average 4 to 5 percent higher than the OLS and SUR models.

Parameter estimates and standard errors for each of the four models discussed are illustrated in Figure **4-6** through Figure **4-9**. The vertical axis displays the parameter values. The error bars display the standard error centered on the parameter estimate. Practical interpretation is provided in Chapter **6**. The remainder of this section summarizes general findings regarding the relationships between speed magnitudes and deviations and work zone geometry and traffic control when only exogenous RHS variables are considered.

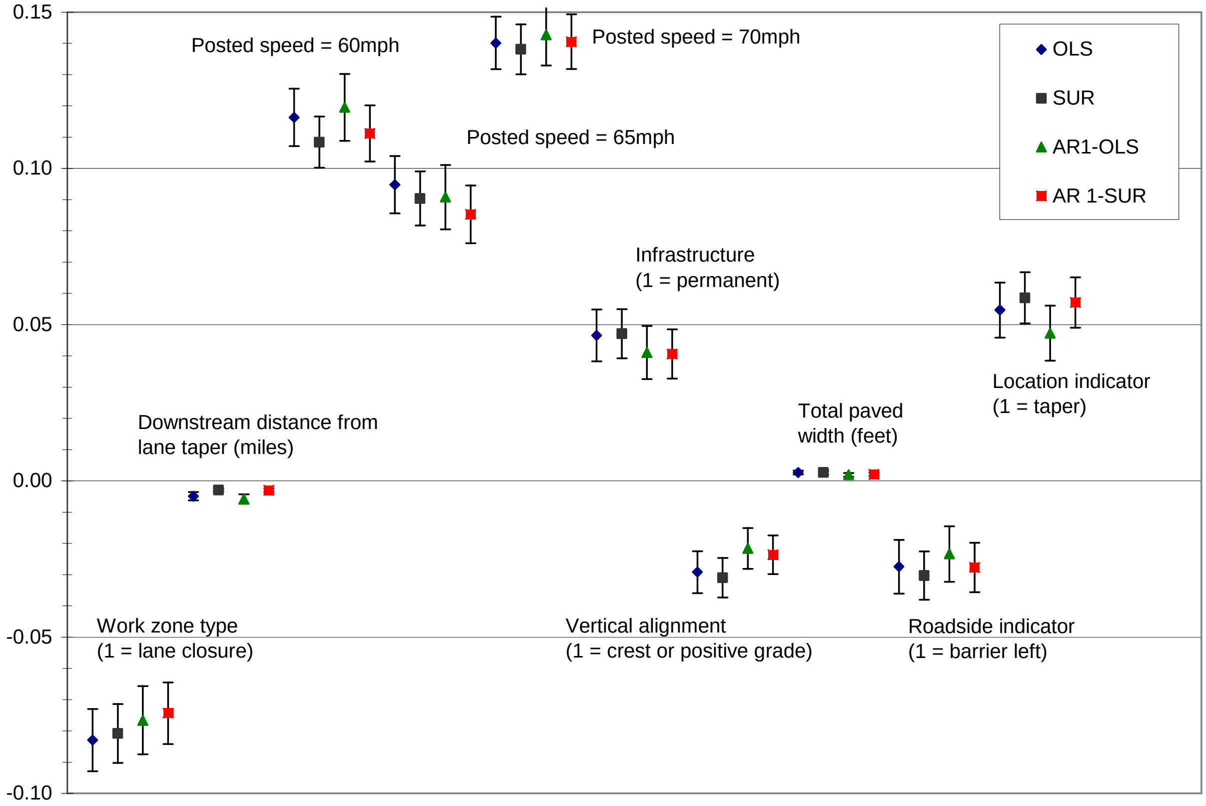

Figure **4-6**: Parameter estimates and standard errors for logarithm of 85th percentile passenger car speed models

Figure **4-7**

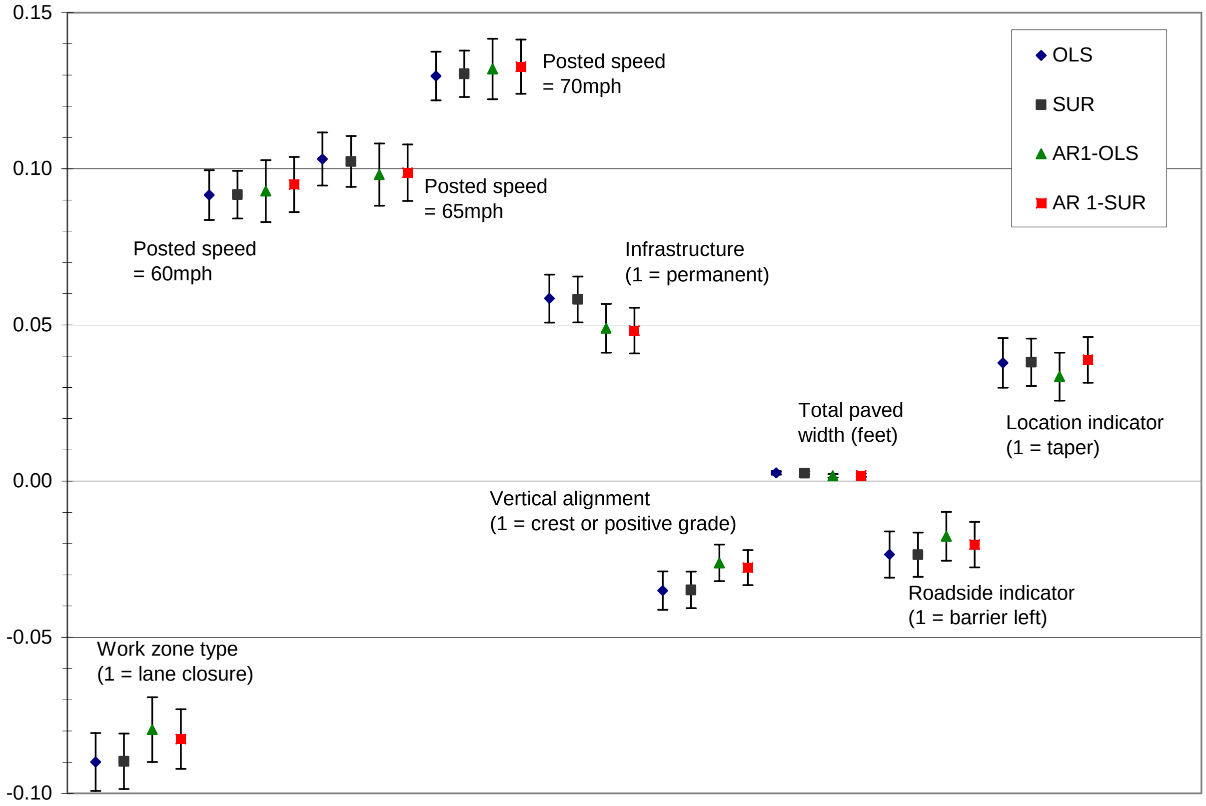

Figure **4-7**: Parameter estimates and standard errors for logarithm of 85th percentile truck speed models

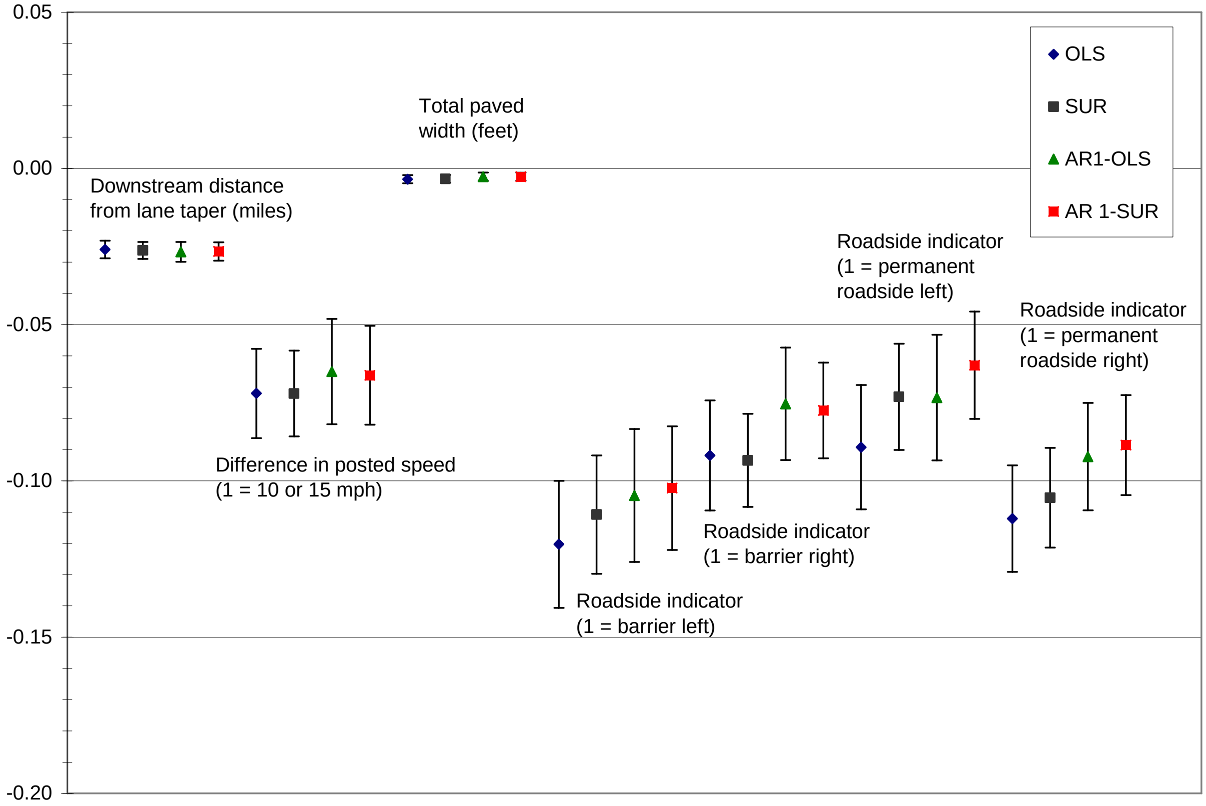

Figure **4-8**: Parameter estimates and standard errors for logarithm of passenger car speed deviation models

Figure **4-9**

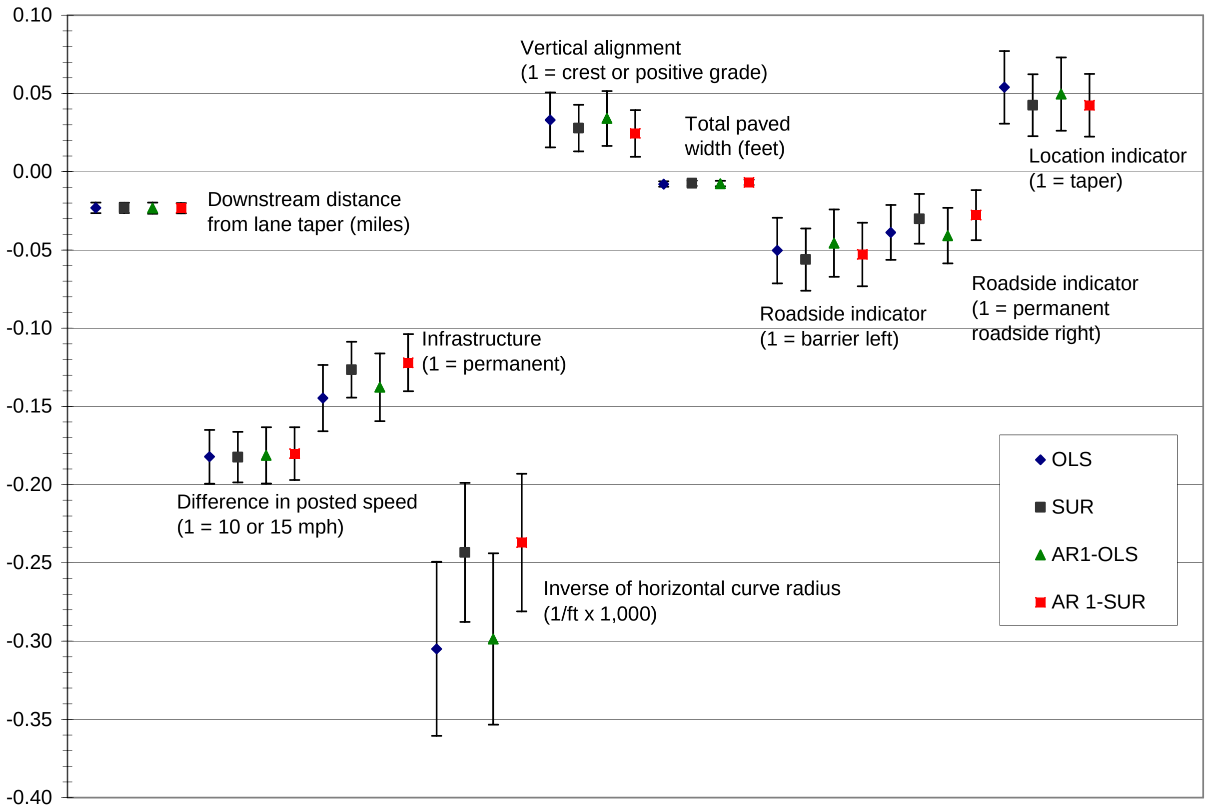

Figure **4-9**: Parameter estimates and standard errors for logarithm of truck speed deviation models

The AR1-SUR model is likely the most appropriate specification given the correlation between the disturbances across equations as well as the presence of positive autocorrelation. The findings from all four models will be discussed jointly, as parameter magnitudes and deviations generally remained stable. Variable-by-variable interpretations of the model parameters follow:

- 85th percentile speeds were slower in work zones with a lane closure strategy (Figure **3-1**) compared to those with a median crossover strategy (Figure **3-3**). This effect was greater for trucks than for passenger cars. Traffic control strategy did not influence speed deviations.
- 85th passenger car speeds as well as speed deviations for both cars and trucks decreased as the distance traveled in the work zone (measured by the downstream distance from the lane taper) increased. The magnitude of the speed deviation effect was similar for both cars and trucks. Distance traveled in the work zone did not influence 85th percentile truck speeds.
- An increase in work zone posted speed was associated with an increase in 85th percentile speeds. The increase was not linear for passenger cars or trucks. Speed deviation for both passenger cars and trucks were lowest in work zones where the posted speed was reduced by 10 or 15 mph from upstream conditions (compared to no reduction in posted speed). This effect was approximately twice as large for trucks as for passenger cars.
- 85th percentile speeds were higher in areas of the work zone where the temporary traveled way used permanent roadway infrastructure compared to areas where temporary infrastructure was built as part of the TTC plan. The magnitude of the effect was similar for both cars and trucks. Truck speed deviations were lower on permanent infrastructure. No influence on car speed deviations was observed.
- The presence of either a positive grade or crest vertical curve was associated with lower 85th percentile speeds for passenger cars and trucks. The magnitude of the effect was very similar for both vehicle types. In addition, a positive grade or crest vertical curve was associated with higher truck speed deviations.

- An increase in total paved width was associated with an increase in 85th percentile speeds and a decrease in speed deviations for both passenger cars and trucks. The magnitudes of the effects were similar for both vehicle types.
- The presence of a temporary concrete barrier to the left of the traveled way tended to decrease 85th percentile speeds for both passenger cars and trucks by a similar magnitude. In general, speed deviations for both passenger cars and trucks were lower in areas where there was either a temporary barrier or no traffic control device (compared to the presence of vertical panels, drums or other similar devices). The magnitudes of the individual effects of these roadside conditions were different for passenger cars and trucks.
- A decrease in horizontal curve radius was associated with a decrease in truck speed deviation.
- 85th percentile speeds were higher in the lane taper than in the remainder of the work zone. The magnitude of the effect was slightly larger for passenger cars. Truck speed deviation was higher in the lane taper than the remainder of the work zone. No influence on car speed deviation was observed.

The combination of inherent differences between passenger cars and trucks with, in some cases, similar speed findings (both in parameter magnitudes and directions) indicate that there may be associations between 85th percentile speeds and speed deviations for passenger cars and trucks. The models in Chapter **5** investigate this hypothesis.

Chapter 5

Simultaneous Equation Models

Model specifications in Chapter **4** included only exogenous RHS variables. The exogenous-only specifications are consistent with most models of speed and highway geometrics. System estimation using SUR resulted in efficiency gains over equation-by-equation OLS. In SUR, the four speed equations (see Eq. **4.8** through Eq. **4.11**) were linked only through their disturbance terms. Two previous studies considered not only the contemporaneous correlation between disturbances, but also inter-relationships between speed magnitudes and deviations through a system of simultaneous equations [**54**], [**55**]. The OLS and SUR results in Chapter **4** indicated these inter-relationships may also exist between 85th percentile speeds and speed deviations for passenger cars and trucks in work zones.

This chapter summarizes estimation results of simultaneous equation models. With both exogenous and endogenous RHS variables, the models take the more general form of Eq. **3.1** through Eq. **3.4**. Three least squares estimators were investigated:

- Two-stage least squares (2SLS);
- Three-stage least squares (3SLS); and
- Ordinary least squares (OLS).

In addition, two models to account for positive autocorrelation were estimated:

- First order autoregressive models with 2SLS; and
- 3SLS with lagged RHS speed variables.

The chapter concludes with a summary of statistical findings.

5.1 Estimation of Simultaneous Equation Models

Estimation of simultaneous equation models was used to test hypotheses regarding contemporaneous inter-relationships between 85th percentile passenger car speed, 85th percentile truck speed and respective speed deviations. The system equations take the log-linear functional form for reasons identified in **4.2**. Preliminary testing, specification and identification issues led to zero restrictions of regression parameters between 85th percentile speeds for one vehicle type (i.e. car or truck) and speed deviations for the other vehicle type. The following general model structure resulted:

Eq. **5.1**

$$\ln s_c = \alpha_{sc} + X_{sc}\beta_{sc} + \gamma_{sc1}\ln s_t + \gamma_{sc2}\ln d_c + \varepsilon_{sc} \qquad \textbf{5.1}$$

Eq. **5.2**

$$\ln s_t = \alpha_{st} + X_{st}\beta_{st} + \gamma_{st1}\ln s_c + \gamma_{st2}\ln d_t + \varepsilon_{st} \qquad \textbf{5.2}$$

Eq. **5.3**

$$\ln d_c = \alpha_{dc} + X_{dc}\beta_{dc} + \gamma_{dc1}\ln s_c + \gamma_{dc2}\ln d_t + \varepsilon_{dc} \qquad \textbf{5.3}$$

Eq. **5.4**

$$\ln d_t = \alpha_{dt} + X_{dt}\beta_{dt} + \gamma_{dt1}\ln s_t + \gamma_{dt2}\ln d_c + \varepsilon_{dt} \qquad \textbf{5.4}$$

The endogenous LHS variables are determined simultaneously in the data-generating process. Endogenous RHS variables are likely contemporaneously correlated with the disturbance term in the same equation as well as other equations. For example, a change in the disturbance term ε_{sc} directly results in a change in $\ln s_c$. Since $\ln s_c$ is a RHS variable in Eq. **5.2**, then $\ln s_t$ also changes as the LHS variable in Eq. **5.2** and as a RHS variable in Eq. **5.1**. Therefore, a change in the disturbance term ε_{sc} results in a change in $\ln s_t$; the two terms are contemporaneously correlated. This violation of the exogeneity assumption (see Table **4-1**) results in biased OLS estimates. The simultaneous equation bias is applicable to parameters in both β and γ. Alternative estimators are usually, but not always, thought necessary [**57**].

The regression coefficients in Eq. **5.1** through Eq. **5.4** (β and γ) are the structural parameters of the model. The equations can be rearranged (by substitution) so that only endogenous variables appear on the LHS and only exogenous variables appear on the RHS. For example, the reduced form equation for 85th percentile passenger car speed is:

Eq. **5.5**

$$\ln s_c = \pi_1 + x_1\pi_2 + x_2\pi_3 + x_3\pi_4 + \ldots + x_n\pi_n + v_{sc} \qquad \mathbf{5.5}$$

where: x_i = exogenous variables appearing in any of the four structural equations;

π_i = reduced form regression coefficients that are non-linear functions of the structural parameters; and

v_{sc} = disturbance for reduced form equation that is a non-linear function of the structural parameters and structural disturbances.

In this example, the RHS variables in Eq. **5.5** are exogenous variables appearing in any of the four structural equations because Eq. **5.1** is directly influenced by Eq. **5.2** and Eq. **5.3** (through $\ln s_t$ and $\ln d_c$) and indirectly influenced by Eq. **5.4** (through $\ln d_c$). OLS provides consistent estimates of π_i since the reduced form has only exogenous RHS variables. Estimating structural parameters is important to gain insights into the underlying data generating process. Reduced-form coefficients are important in forecasting or policy-influencing contexts. Both parameter types are reported for the models in this chapter.

5.1.1 Identification

Using reduced form parameters to estimate structural parameters is one way to estimate a system of simultaneous equations. The operation is a mathematical, as opposed to statistical problem analogous to solving for a given number of unknowns using a given number of equations. Determination of whether this can be done is made equation-by-equation.

If the structural parameters can be estimated from the reduced form parameters, then an equation is *identified*. In a *just-identified* equation, there is only one solution for the structural parameters given the reduced form parameters (i.e. the number of equations equals the number of unknowns). If an equation is *over-identified* (i.e. more equations than unknowns), then there is not an exact solution and a statistical criterion (e.g. least squares) is applied. If an equation is not identified, or *under-identified*, then the structural parameters cannot be estimated from the reduced form. An infinite number of solutions exist in the under-identified case because the number of unknowns is greater than the number of equations. Each equation must be identified or over-identified for the entire system to be identified.

The rank and order conditions require minimal mathematical work and can be used to determine the identification of a system. The conditions are tested for each equation. The rank condition is a restriction placed on the reduced-form coefficient matrix of the variables not included in the equation being investigated. Specifically, that

Eq. **5.6**

$$rank[\Pi_j^*] = M_j \qquad \textbf{5.6}$$

where: j = subscript for the equation being tested for the rank condition;

Π_j^* = a sub-matrix of the reduced form coefficient matrix for equation j (i.e. the reduced-form coefficient matrix of the variables not included in the equation j); and

M_j = number of RHS endogenous variables in equation j .

Details of the rank condition test are illustrated in **5.2** (see Figure **5-1**).

The order condition is a restriction that the number of exogenous variables excluded from the equation being investigated must be at least as large as the number of RHS endogenous variables in the equation (see Eq. **5.7**).

Eq. **5.7**

$$K_j^* \geq M_j \qquad \textbf{5.7}$$

where: j = subscript for the equation being tested for the order condition;

K_j^* = the number of exogenous variables excluded from equation j ; and

M_j = the number of RHS endogenous variables in equation j).

Each equation must meet both rank and order conditions to be identified. Three possible cases are summarized in Table **5-1**.

Table **5-1**

Table **5-1**: Cases of equation identification

Case	Results of rank and order tests
Under-identified	$K_j^* < M_j$ or rank condition fails
Exactly-identified	$K_j^* = M_j$ and the rank condition is met
Over-identified	$K_j^* > M_j$ and the rank condition is met

The least squares estimators of simultaneous equation models (2SLS and 3SLS) do not directly use the reduced form parameters to estimate the structural parameters. However, the concept of identification is still important. In some cases, structural parameters may be computed for systems that are not identified. In the case of 2SLS and 3SLS, the estimates will not be consistent [**60**]. For the just-identified condition, less computationally intensive estimators (e.g. indirect least squares) will give the same results as 2SLS and 3SLS.

5.2 Two-Stage Least Squares Estimation

The simultaneous equation bias of OLS that arises from correlation between endogenous RHS variables and the disturbance terms was discussed in **5.1**. One possible solution is to create a new variable for each endogenous RHS variable that is:

- Highly correlated with the endogenous variable; and
- Contemporaneously uncorrelated with the disturbance.

The new variable is an *instrumental variable* (or *instrument*) for the endogenous RHS variable. Choices for the instrument include other exogenous variables or linear combinations of exogenous variables. Estimation using instrumental variables is more efficient the higher the correlation between the instruments and the respective endogenous variables.

In the absence of heteroscedasticity or autocorrelation, the most efficient estimator results when instruments are created by regressing the endogenous RHS variables against all exogenous variables in the system with OLS and using the predicted values as the instrument. This is expressed by:

Eq. **5.8**

$$\hat{Y}_j = X\left[\left(X'X\right)^{-1} X'Y_j\right] \qquad \textbf{5.8}$$

where: Y_j = an n x M_j matrix of endogenous RHS variables in equation j;

X = an n x k matrix of all exogenous variables in the system; and

$\hat{Y}_j$ = an n x M_j matrix of instruments for the endogenous RHS variables in equation j.

The 2SLS estimator consists of creating the instruments ($\hat{Y}_j$) for endogenous RHS variables of each equation in the system, then regressing the LHS dependent variable (y_j) on the instruments and the exogenous variables specified in that equation (i.e., $\hat{Y}_j$ and X_j) with OLS. Details of 2SLS are shown in Eq. **5.9**.

Eq. **5.9**

$$\hat{\delta}_{2SLS} = \begin{bmatrix} g_j \\ b_j \end{bmatrix} = \begin{bmatrix} \hat{Y}_j'\hat{Y}_j & \hat{Y}_j'X_j \\ X_j'\hat{Y}_j & X_j'X_j \end{bmatrix}^{-1} \begin{bmatrix} \hat{Y}_j'y_j \\ X_j'y_j \end{bmatrix} \qquad \textbf{5.9}$$

where: $\hat{\delta}_{2SLS}$ = 2SLS parameter estimates;

g_j = 2SLS parameter estimates for instruments in equation *j*;

b_j = 2SLS parameter estimates for exogenous variables in equation *j*;

$\hat{Y}_j$ = instruments for the endogenous RHS variables in equation *j*;

X_j = exogenous variables in equation *j*; and

y_j = LHS endogenous variable in equation *j*.

Two-stage least squares is a limited-information method because it estimates parameters equation-by-equation. Similar to comparisons between OLS and SUR in Chapter **4**, the 2SLS estimator is consistent but not efficient if there are contemporaneous correlations between the disturbances. However, it also has an important advantage. Monte Carlo studies have shown 2SLS to be quite robust in the presence of some specification errors [**57**]. It is therefore the most widely used estimator of simultaneous equation models [**57**].

Two-stage least squares was used to estimate the structural parameters in Eq. **5.1** through Eq. **5.4**. The OLS specifications in Table **4-7** through Table **4-10** were used as a starting point for specification of exogenous RHS variables in each equation. In addition, the endogenous RHS specifications identified in Eq. **5.1** through Eq. **5.4** were tested. Variables were eliminated from the RHS if they showed no association with the LHS variable. Results of the 2SLS estimations are summarized in Table **5-2** through Table **5-5**. The tables show estimated structural parameters ($\hat{\delta}_{2SLS}$) and standard errors (S.E. $\{\hat{\delta}_{2SLS}\}$), t-statistics (*t*) and reduced form parameters ($\hat{\pi}$). The following model statistics are also reported:

- Residual Sum of Squared Errors (*SSE*);
- R-squared (R^2);
- Adjusted R-squared (R^2_{adj}); and
- Durbin-Watson statistic for first order serial correlation (*DW*).

The number of observations used for model estimation (*N*) is also provided.

Model parameters are discussed in detail in **5.6**. General observations were:

- The system of simultaneous equations appeared to be a better representation of the data generating process than the exogenous-only OLS and SUR models in Chapter **4**.
- The relationship between 85th percentile passenger car speed and 85th percentile truck speed is simultaneous.
- The relationship between 85th percentile passenger car speed and passenger car speed deviation is simultaneous.
- The relationship between 85th percentile truck speed and truck speed deviation is recursive and opposite (in sign) to that of passenger cars.
- The relationship between passenger car speed deviation and truck speed deviation was simultaneous and positive in sign.
- The exogenous RHS variables are the same (in sign) but smaller (in magnitude) than respective parameters in the Chapter **4** OLS and SUR models.
- Work zone geometry and traffic control elements are not directly associated with 85th percentile passenger car speeds; they are indirectly associated with them through truck speeds and car speed deviations.

Table **5-2**

Table **5-2**: 2SLS estimates for logarithm of 85th percentile passenger car speed

	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$	t	$\hat{\pi}$
Constant	-0.1738	0.1652	-1.05	4.0527
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0198	0.0072	2.76	0.0578
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-0.0889
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.1203
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	0.0857
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.1314
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	0.0424
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-0.0271
Total paved width (ft)	-----	-----	-----	0.0021
Downstream distance from lane taper (mile)	-----	-----	-----	-0.0052
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0331
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0089
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.0057
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.0085
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0153
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0125
Logarithm of 85th percentile truck speed	1.0253	0.0385	26.61	
Logarithm of car speed deviation	0.0620	0.0193	3.22	
$N = 119$; $SSE = 0.0833$; $R^2 = 0.916$; $R^2_{adj} = 0.913$; $DW = 1.76$ [1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)				

Table **5-3**

Table **5-3**: 2SLS estimates for logarithm of 85th percentile truck speed

	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$	t	$\hat{\pi}$
Constant	1.6696	0.3249	5.14	3.9989
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.0360
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.0403	0.0091	-4.43	-0.0929
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0315	0.0110	2.87	0.0966
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0487	0.0111	4.37	0.0961
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.0500	0.0136	3.67	0.1206
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0297	0.0086	3.47	0.0519
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0154	0.0063	-2.45	-0.0333
Total paved width (ft)	0.0011	0.0006	1.76	0.0024
Downstream distance from lane taper (mile)	-----	-----	-----	-0.0021
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0142
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0113
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	0.0088
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.0082
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0103
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0268
Logarithm of 85th percentile car speed	0.5761	0.0822	7.01	

$N = 119$; $SSE = 0.0829$; $R^2 = 0.898$; $R^2_{adj} = 0.891$; $DW = 1.50$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-4**: 2SLS estimates for logarithm of passenger car speed deviation

	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$	t	$\hat{\pi}$
Constant	0.0915	0.6529	0.14	1.8752
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.0195
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----	-----	-----	0.0100
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.0372
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	0.0104
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.1287
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-0.0207
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.0342
Total paved width (ft)	-0.0038	0.0024	-1.62	-0.0052
Downstream distance from lane taper (mile)	-0.0179	0.0055	-3.27	-0.0276
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1023	0.0382	-2.68	-0.1528
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0789	0.0297	-2.66	-0.0646
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0848	0.0339	-2.50	-0.1174
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0791	0.0297	-2.66	-0.0931
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0116
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0201
Logarithm of 85th percentile car speed	0.2861	0.1608	1.78	
Logarithm of truck speed deviation	0.3748	0.1163	3.22	

$N = 119$; $SSE = 1.477$; $R^2 = 0.626$; $R^2_{adj} = 0.599$; $DW = 1.70$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-5**

Table **5-5**: 2SLS estimates for logarithm of truck speed deviation

	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$	t	$\hat{\pi}$
Constant	3.6943	1.0643	3.47	1.8991
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0772	0.0431	1.79	0.0612
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	0.0456
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-0.0507
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-0.0600
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.0096
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1189	0.0403	-2.95	-0.1442
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.0374
Total paved width (ft)	-0.0050	0.0034	-1.46	-0.0073
Downstream distance from lane taper (mile)	-0.0142	0.0095	-1.50	-0.0192
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0397
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0111
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.0163
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0450	0.0340	-1.32	-0.0511
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1898	0.0362	-5.25	-0.1615
Inverse of horizontal curve radius (1/ft x 1000)	-0.3193	0.1039	-3.07	-0.2960
Logarithm of 85th percentile truck speed	-0.5541	0.2350	-2.36	
Logarithm of car speed deviation	0.2522	0.2370	1.06	

$N = 119$; $SSE = 2.238$; $R^2 = 0.579$; $R^2_{adj} = 0.544$; $DW = 1.87$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Identification of each equation in Table **5-2** through Table **5-5** was checked. All equations were over-identified. An example of the rank condition check for 85th percentile passenger car speed is shown in Figure **5-1**. The results of rank and order identification checks for all four equations are summarized in Table **5-6**.

Figure **5-1**

Step 1: Create a system matrix of exogenous variables which indicates whether the parameter for each exogenous variable is included (1) or restricted to zero (0):

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
s_c	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_t	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0
d_c	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
d_t	1	0	0	0	0	1	0	1	1	0	0	0	1	1	1

Step 2: Eliminate the row representing the equation being checked and rows representing endogenous variables that are not included as RHS variables in the equation being checked. In addition, delete the columns representing the variables included in the equation being checked.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
s_c	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_t	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0
d_c	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
d_t	1	0	0	0	0	1	0	1	1	0	0	0	1	1	1

Step 3: The remaining matrix has the same rank as the sub-matrix of the reduced form coefficient matrix. Check the rank of the matrix against the number of RHS endogenous variables.

$rank[\Pi_j^*] = 2 = M_j = 2$ (equation meets the rank condition)

Figure **5-1**: Example of rank condition check for 85th percentile passenger car speed equation

Table **5-6**

Table **5-6**: Summary of rank and order checks for identification

Equation	M_j	K_j^*	Order	$rank[\Pi_j^*]$	Rank
$\ln s_c$	2	14	Over-identified	2	√
$\ln s_t$	1	8	Over-identified	1	√
$\ln d_c$	2	9	Over-identified	2	√
$\ln d_t$	2	8	Over-identified	2	√

The instruments that were created for each endogenous variable were also checked against the desirable properties of instrumental variables:

- Highly correlated with the endogenous variable for which it is an instrument; and
- Contemporaneously uncorrelated with the disturbance.

The results are summarized in Table **5-7**. The instruments have strong correlations with the endogenous variables (all greater than 0.73) and are uncorrelated with the disturbances of the equations in which they are RHS variables.

Table **5-7**

Table **5-7**: Properties of instrumental variables

Endogenous variable	$r(y,\hat{y})$	$r(\hat{y},e_{sc})$	$r(\hat{y},e_{st})$	$r(\hat{y},e_{dc})$	$r(\hat{y},e_{dt})$
$\ln s_c$	0.79	n/a	0.00	0.00	n/a
$\ln s_t$	0.79	0.00	n/a	n/a	0.00
$\ln d_c$	0.74	0.00	n/a	n/a	0.00
$\ln d_t$	0.73	n/a	n/a	0.00	n/a

$r(y,\hat{y})$ = correlation between endogenous variable and its instrument

$r(\hat{y},e_i)$ = correlation between instrument and respective equation disturbance

5.3 Three-Stage Least Squares Estimation

Estimating simultaneous equation models as a system with GLS results in efficiency gains if the equation disturbances are contemporaneously correlated. Using residuals from equation-by-equation OLS provides consistent estimates of the elements of the variance-covariance matrix (Σ) for SUR estimation. Similarly, residuals from equation-by-equation 2SLS can be used to estimate elements of Σ for 3SLS.

In 3SLS, the system of simultaneous equations is written as a stacked model illustrated in Eq. **5.10**.

Eq. **5.10**

$$\begin{bmatrix} s_c \\ s_t \\ d_c \\ d_t \end{bmatrix} = \begin{bmatrix} G_{sc} & 0 & 0 & 0 \\ 0 & G_{st} & 0 & 0 \\ 0 & 0 & G_{dc} & 0 \\ 0 & 0 & 0 & G_{dt} \end{bmatrix} \begin{bmatrix} \delta_{sc} \\ \delta_{st} \\ \delta_{dc} \\ \delta_{dt} \end{bmatrix} + \begin{bmatrix} \varepsilon_{sc} \\ \varepsilon_{st} \\ \varepsilon_{dc} \\ \varepsilon_{dt} \end{bmatrix} = G_* \delta_* + \varepsilon_* \qquad \mathbf{5.10}$$

G_* consists of both exogenous and endogenous RHS variables. For each endogenous variable Y_i in the matrix G_* , an instrument can be created by:

Eq. **5.11**

$$\overset{\wedge}{Y_i} = X\left[(X'X)^{-1} X'Y_i\right] \qquad \mathbf{5.11}$$

where: Y_i = an endogenous variable in matrix G ;

X = all exogenous variables in the system; and

$\overset{\wedge}{Y_i}$ = instrument for Y_i .

If the endogenous variables in G_* are replaced with their respective instruments, then the stacked model becomes:

Eq. **5.12**

$$\begin{bmatrix} s_c \\ s_t \\ d_c \\ d_t \end{bmatrix} = \begin{bmatrix} \hat{G}_{sc} & 0 & 0 & 0 \\ 0 & \hat{G}_{st} & 0 & 0 \\ 0 & 0 & \hat{G}_{dc} & 0 \\ 0 & 0 & 0 & \hat{G}_{dt} \end{bmatrix} \begin{bmatrix} \delta_{sc} \\ \delta_{st} \\ \delta_{dc} \\ \delta_{dt} \end{bmatrix} + \begin{bmatrix} \varepsilon_{sc} \\ \varepsilon_{st} \\ \varepsilon_{dc} \\ \varepsilon_{dt} \end{bmatrix} = \hat{G}_* \delta_* + \varepsilon_* \qquad \textbf{5.12}$$

where $\hat{G}_*$ consists of both exogenous variables and instruments.

Given these definitions, the three steps of three-stage least squares are summarized in Figure **5-2**.

Figure **5-2**

Step 1. Define $\hat{G}_*$ by creating instruments for endogenous RHS variables using OLS (see Eq. **5.11**).

Step 2. For each equation *j*, compute 2SLS estimates by:

Eq. **5.13**

$$\hat{\delta}_{2SLS} = \begin{bmatrix} \hat{G}_j'\hat{G}_j & \hat{G}_j'X_j \\ X_j'\hat{G}_j & X_j'X_j \end{bmatrix}^{-1} \begin{bmatrix} \hat{G}_j'y_j \\ X_j'y_j \end{bmatrix} \qquad \textbf{5.13}$$

Use the 2SLS residuals to estimate elements of Σ (see Eq. **4.13**) [Note: actual values of endogenous RHS variables are used to compute the residuals].

Step 3. Estimate δ_* with the GLS estimator:

Eq. **5.14**

$$\hat{\delta}_{3SLS} = \left(\hat{G}_*'\Omega^{-1}\hat{G}_* \right)^{-1} \hat{G}'\Omega^{-1}y \qquad \textbf{5.14}$$

Note: matrix Ω was previously defined in Eq. **4.14**.

Figure **5-2**: Steps of 3SLS

There is no formal statistical test to determine if 3SLS is superior to 2SLS. Similar to SUR, efficiency gains will result if the variance-covariance matrix, Ω , is not diagonal. Kennedy identified a rule of thumb that 3SLS is superior if the contemporaneous correlation between the errors of any two equations exceeds one-third [**57**]. The estimated correlations using the 2SLS specifications in Table **5-2** through Table **5-5** are provided in Eq. **5.15**.

Eq. **5.15**

$$r(e_i, e_j) = \begin{bmatrix} 1 & -0.550 & -0.174 & -0.391 \\ -0.550 & 1 & -0.177 & 0.336 \\ -0.174 & -0.177 & 1 & -0.162 \\ -0.391 & 0.336 & -0.162 & 1 \end{bmatrix} \qquad \mathbf{5.15}$$

Magnitudes of the correlations indicate that efficiency will be gained with 3SLS compared to 2SLS. Results of 3SLS estimation as well as comparisons to 2SLS parameters and standard errors are provided in Table **5-8** through Table **5-11**. The OLS specifications in Table **4-7** through Table **4-10** were again used as a starting point for specifying the exogenous RHS variables in each equation. The RHS endogenous specifications identified in Eq. **5.1** through Eq. **5.4** were initially tested. Variables were eliminated from the RHS if they showed no association with the LHS variable. Using this procedure, the 3SLS specifications generally converged to the 2SLS specifications. Standard errors of parameter estimates decreased by anywhere from approximately 1to 18 percent, with an average 8 percent decrease compared to 2SLS. The reduced form coefficients are the same as for the 2SLS models and are not included in the 3SLS tables.

Table **5-8**

Table **5-8**: 3SLS estimates for logarithm of 85th percentile passenger car speed

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	-0.1779	0.1612	-0.1738	0.1652
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0190	0.0063	0.0198	0.0072
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-----	-----	-----	-----
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile truck speed	1.0274	0.0380	1.0253	0.0385
Logarithm of car speed deviation	0.0592	0.0174	0.0620	0.0193

$N = 119$; $SSE = 0.0827$; $R^2 = 0.916$; $R^2_{adj} = 0.914$; $DW = 1.76$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-9**

Table **5-9**: 3SLS estimates for logarithm of 85th percentile truck speed

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	1.4980	0.3000	1.6696	0.3249
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.0315	0.0079	-0.0403	0.0091
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0338	0.0097	0.0315	0.0110
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0360	0.0096	0.0487	0.0111
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.0439	0.0120	0.0500	0.0136
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0215	0.0071	0.0297	0.0086
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0110	0.0052	-0.0154	0.0063
Total paved width (ft)	0.0011	0.0005	0.0011	0.0006
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.6188	0.0755	0.5761	0.0822

$N = 119$; $SSE = 0.0777$; $R^2 = 0.904$; $R^2_{adj} = 0.897$; $DW = 1.45$

[1] preliminary testing showed structural parameter not statistically significant ($p\text{-value} > 0.33$)

Table **5-10**

Table **5-10**: 3SLS estimates for logarithm of passenger car speed deviation

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	-0.0150	0.6477	0.0915	0.6529
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0036	0.0023	-0.0038	0.0024
Downstream distance from lane taper (mile)	-0.0175	0.0052	-0.0179	0.0055
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1037	0.0355	-0.1023	0.0382
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0668	0.0274	-0.0789	0.0297
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0757	0.0313	-0.0848	0.0339
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0651	0.0278	-0.0791	0.0297
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.3091	0.1592	0.2861	0.1608
Logarithm of truck speed deviation	0.3717	0.1115	0.3748	0.1163

$N = 119$; $SSE = 1.487$; $R^2 = 0.624$; $R^2_{adj} = 0.597$; $DW = 1.66$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-11**

Table **5-11**: 3SLS estimates for logarithm of truck speed deviation

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	2.9789	1.0270	3.6943	1.0643
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0684	0.0406	0.0772	0.0431
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1223	0.0361	-0.1189	0.0403
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0039	0.0031	-0.0050	0.0034
Downstream distance from lane taper (mile)	-0.0090	0.0086	-0.0142	0.0095
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0174	0.0309	-0.0450	0.0340
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1563	0.0328	-0.1898	0.0362
Inverse of horizontal curve radius (1/ft x 1000)	-0.2563	0.0927	-0.3193	0.1039
Logarithm of 85th percentile truck speed	-0.4879	0.2292	-0.5541	0.2350
Logarithm of car speed deviation	0.4914	0.2163	0.2522	0.2370

N = 119; *SSE* = 2.105; $R^2 = 0.604$; $R^2_{adj} = 0.571$; *DW* = 1.87

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

5.4 Ordinary Least Squares Estimation

In some cases, the asymptotic simultaneous equation bias of OLS is accepted for a possible decrease in mean square error compared to 2SLS and 3SLS. Additional defenses of using OLS in a simultaneous equation context were provided by Kennedy [**57**]:

- OLS has minimum variance compared to alternative estimators.
- In small samples, 2SLS and 3SLS are also biased.
- In small samples, the properties of the OLS estimator are less sensitive to multicollinearity, errors in variables and misspecifications than alternative estimators.
- Predictions from simultaneous equation models estimated by OLS often compare favorably with predictions from models estimated by alternative means.

Greene acknowledged some of these points but countered them with the finding that OLS standard errors are most likely not useful for inference purposes [**60**].

The specifications in **5.2** and **5.3** were estimated with OLS for comparison purposes. Details of the OLS estimator are provided in Table **4-10 .** Endogenous RHS variables were specified in their original form (i.e., not as instruments). Results are summarized in Table **5-12** through Table **5-15**. A comparison to 3SLS parameters and standard errors is also provided. The SSE for models of 85th percentile car and truck speeds decreased by 2 and 12 percent respectively compared to 3SLS. SSE increased by approximately 7 percent for both speed deviation models. The estimate of the constant term for car speed deviation changed in sign. Other parameter estimates kept the same sign but changed in magnitude by anywhere from a 93 percent decrease to a 40 percent increase. Similarly, both increases and decreases in standard errors were observed.

Table **5-12**

Table **5-12**: OLS estimates for logarithm of 85th percentile passenger car speed

	$\hat{\delta}_{OLS}$	S.E. $\{\hat{\delta}_{OLS}\}$	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$
Constant	-0.0119	0.1240	-0.1779	0.1612
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0258	0.0066	0.0190	0.0063
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-----	-----	-----	-----
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile truck speed	0.9989	0.0293	1.0274	0.0380
Logarithm of car speed deviation	0.0274	0.0135	0.0592	0.0174

$N = 119$; $SSE = 0.0813$; $R^2 = 0.920$; $R^2_{adj} = 0.918$; $DW = 1.72$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-13**

Table **5-13**: OLS estimates for logarithm of 85th percentile truck speed

	$\hat{\delta}_{OLS}$	S.E. $\{\hat{\delta}_{OLS}\}$	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$
Constant	0.8478	0.1407	1.6696	0.3249
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.0303	0.0076	-0.0403	0.0091
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0113	0.0077	0.0315	0.0110
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0301	0.0082	0.0487	0.0111
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.0213	0.0084	0.0500	0.0136
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0177	0.0068	0.0297	0.0086
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0104	0.0055	-0.0154	0.0063
Total paved width (ft)	0.0001	0.0005	0.0011	0.0006
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.7841	0.0355	0.5761	0.0822

$N = 119$; $SSE = 0.0683$; $R^2 = 0.922$; $R^2_{adj} = 0.917$; $DW = 1.54$

[1] preliminary testing showed structural parameter not statistically significant ($p\text{-}value > 0.33$)

Table **5-14**

Table **5-14**: OLS estimates for logarithm of passenger car speed deviation

	$\hat{\delta}_{OLS}$	S.E. $\{\hat{\delta}_{OLS}\}$	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$
Constant	0.4574	0.5236	-0.0150	0.6477
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0033	0.0024	-0.0036	0.0023
Downstream distance from lane taper (mile)	-0.0176	0.0051	-0.0175	0.0052
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0939	0.0366	-0.1037	0.0355
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0821	0.0304	-0.0668	0.0274
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0820	0.0350	-0.0757	0.0313
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0801	0.0302	-0.0651	0.0278
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.1849	0.1260	0.3091	0.1592
Logarithm of truck speed deviation	0.4006	0.0621	0.3717	0.1115
$N = 119$; $SSE = 1.586$; $R^2 = 0.629$; $R^2_{adj} = 0.602$; $DW = 1.69$ [1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)				

Table **5-15**

Table **5-15**: OLS estimates for logarithm of truck speed deviation

	$\hat{\delta}_{OLS}$	S.E. $\{\hat{\delta}_{OLS}\}$	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$
Constant	2.1865	0.7241	2.9789	1.0270
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0567	0.0418	0.0684	0.0406
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1085	0.0380	-0.1223	0.0361
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0047	0.0032	-0.0039	0.0031
Downstream distance from lane taper (mile)	-0.0083	0.0063	-0.0090	0.0086
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0245	0.0317	-0.0174	0.0309
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1615	0.0314	-0.1563	0.0328
Inverse of horizontal curve radius (1/ft x 1000)	-0.2572	0.0983	-0.2563	0.0927
Logarithm of 85th percentile truck speed	-0.2973	0.1715	-0.4879	0.2292
Logarithm of car speed deviation	0.5061	0.0948	0.4914	0.2163

$N = 119$; $SSE = 2.254$; $R^2 = 0.612$; $R^2_{adj} = 0.580$; $DW = 1.84$

[1] preliminary testing showed structural parameter not statistically significant ($p\text{-}value > 0.33$)

5.5 Investigation of Autocorrelation in the Simultaneous Equation Models

Positive autocorrelation discussed in **4.4** was also apparent in the simultaneous equation models. Durbin-Watson test statistics ranged from 1.54 to 1.84 and residual plots supported these values. Examples of residual plots for logarithms of 85th percentile passenger car and truck speeds, which both illustrate positive autocorrelation, are provided in Figure **5-3** and Figure **5-4**. Two techniques were identified to address the autocorrelation:

- First order autoregressive model estimated with 2SLS (AR1-2SLS); and
- Specification of a lagged speed variable (by one time period) on the RHS.

The AR1 model takes the following form in the simultaneous equation context:

Eq. **5.16**

$$Y_t = \alpha + \beta X_t + \gamma Z_t + \varepsilon_t = \alpha + \beta X_t + \gamma Z_t + \rho \varepsilon_{t-1} + u_t \qquad \mathbf{5.16}$$

where all parameters are the same as previously defined in **4.4** and Z_t is a matrix of endogenous RHS variables. The computational steps of the AR1-2SLS estimator are:

1. Define $\hat{Z}_t$ by creating instruments for the endogenous variables using OLS (see Eq. **5.11**);
2. Regress Y_t on X_t and $\hat{Z}_t$ using OLS.
3. Estimate the disturbance (ε_t) with 2SLS residuals (e_t).
4. Compute the Durbin-Watson test statistic using Eq. **4.19**.
5. Estimate the autocorrelation coefficient with Eq. **4.20**.
6. Regress Y_t^* on X_t^* and $\hat{Z}_t^*$ using OLS. Y_t^* and X_t^* are defined in Eq. **4.21** and:

Eq. **5.17**

$$\hat{Z}_t^* = \begin{bmatrix} \sqrt{1-r^2}\,z_1 \\ z_2 - rz_1 \\ z_3 - rz_2 \\ . \\ . \\ . \\ z_T - rz_{T-1} \end{bmatrix} \qquad \mathbf{5.17}$$

Note: z_i = the ith row of instrument matrix $\hat{Z}$

7. Iterate until value for the autocorrelation coefficient converges.

Figure **5-3**

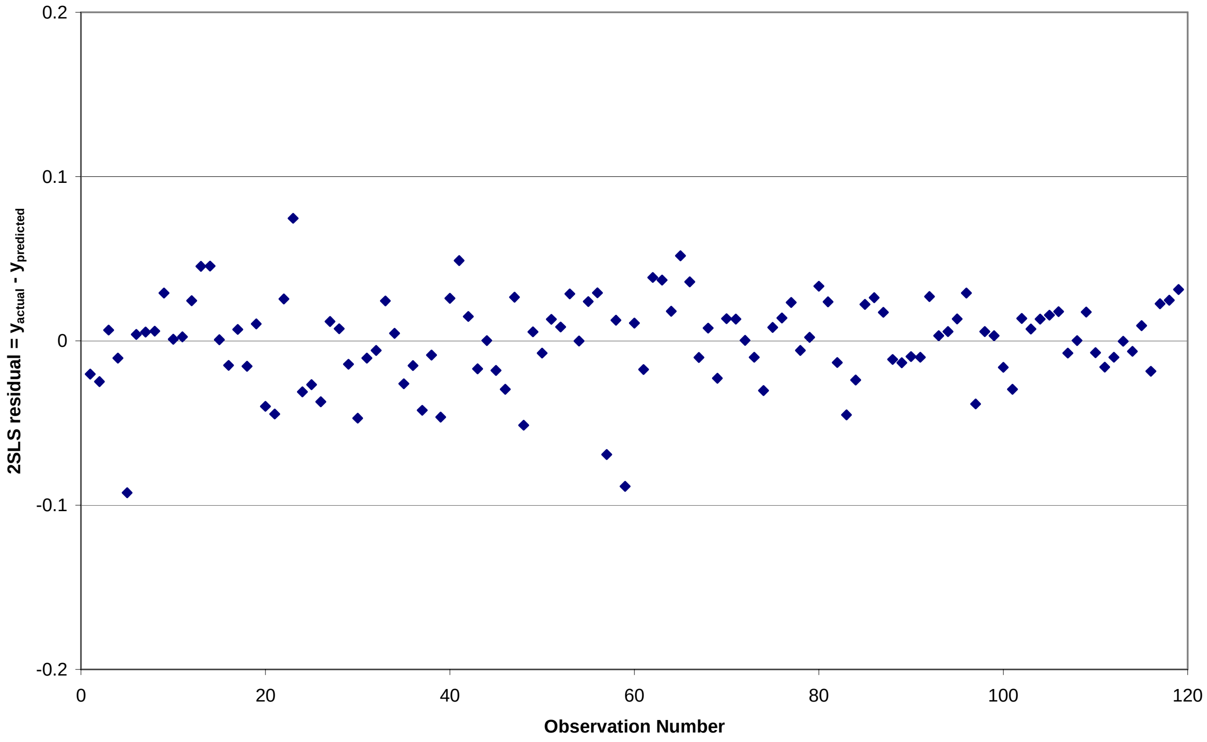

Figure **5-3**: 2SLS residuals for logarithm of 85th percentile passenger car speed

Figure **5-4**

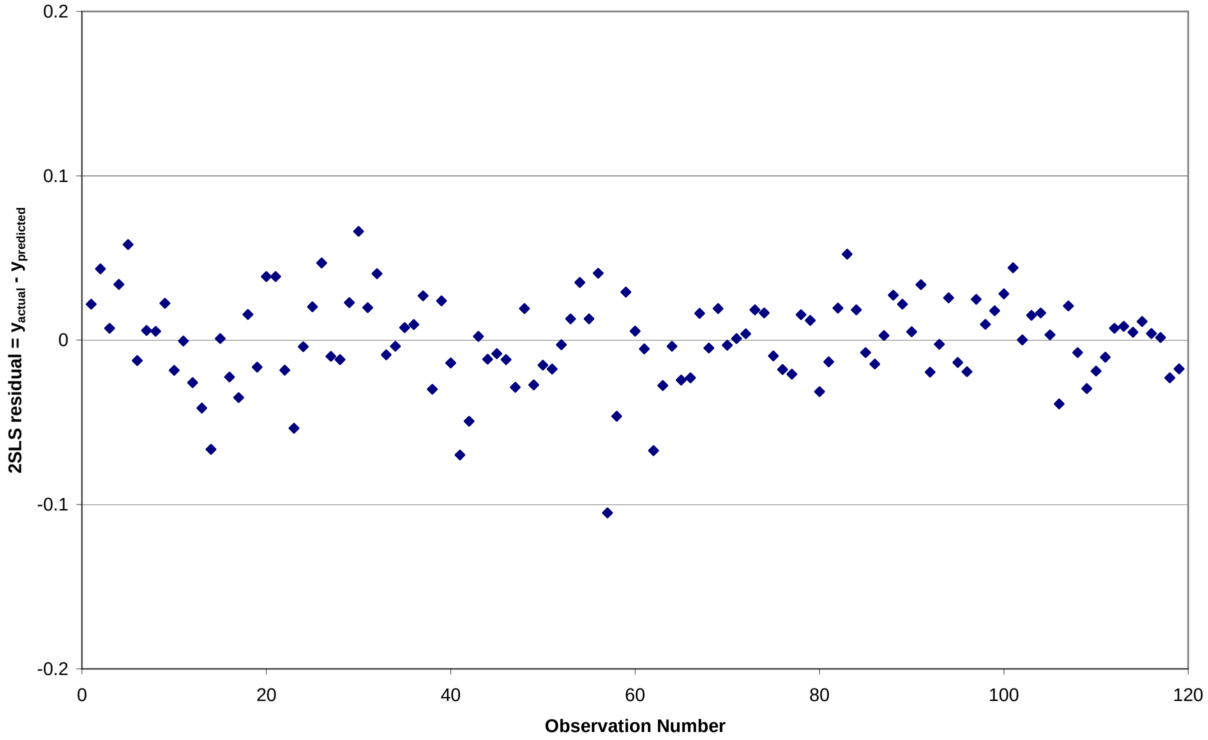

Figure **5-4**: 2SLS residuals for logarithm of 85th percentile truck speed

The results of the AR1-2SLS estimations are summarized in Table **5-16** through Table **5-19**. The tables include parameter estimates and standard errors for the AR1-2SLS models as well as those from traditional 2SLS. Updated estimates of the Durbin-Watson statistics and final estimates of the autocorrelation coefficient are also included. Estimates of the autocorrelation coefficient were statistically significant for logarithm of truck speed and passenger car speed deviation. Estimated parameter standard errors for models of 85th percentile passenger car and truck speeds increased anywhere from 91 to 140 percent compared to 2SLS. Estimated parameter standard errors for the speed deviation models increased anywhere from 9 to 30 percent compared to 2SLS. Parameter estimates also changed by anywhere from a 57 percent decrease to a 105 percent increase. However, the signs of all estimates stayed constant.

Table **5-16**

Table **5-16**: AR1-2SLS estimates for logarithm of 85th percentile passenger car speed

	$\hat{\delta}_{2SLS}^{AR1}$	S.E. $\{\hat{\delta}_{2SLS}^{AR1}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	-0.0736	0.3966	-0.1738	0.1652
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0135	0.0159	0.0198	0.0072
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-----	-----	-----	-----
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile truck speed	0.9955	0.0925	1.0253	0.0385
Logarithm of car speed deviation	0.0767	0.0460	0.0620	0.0193
RHO	0.1398	0.0912		

AR1: $N = 119$; $DW = 2.03$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-17**

Table **5-17**: AR1-2SLS estimates for logarithm of 85th percentile truck speed

	$\hat{\delta}^{AR1}_{2SLS}$	S.E. $\{\hat{\delta}^{AR1}_{2SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	1.8742	0.6946	1.6696	0.3249
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.0368	0.0212	-0.0403	0.0091
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0386	0.0252	0.0315	0.0110
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0488	0.0253	0.0487	0.0111
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.0596	0.0305	0.0500	0.0136
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0230	0.0184	0.0297	0.0086
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0099	0.0121	-0.0154	0.0063
Total paved width (ft)	0.0004	0.0013	0.0011	0.0006
Downstream distance from lane taper (mile)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-----
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.5296	0.1756	0.5761	0.0822
RHO	0.2492	0.0892		

AR1: $N = 119$; $DW = 1.98$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-18**: AR1-2SLS estimates for logarithm of passenger car speed deviation

	$\hat{\delta}_{2SLS}^{AR1}$	S.E. $\{\hat{\delta}_{2SLS}^{AR1}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	0.1882	0.8550	0.0915	0.6529
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-----
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-----
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0028	0.0028	-0.0038	0.0024
Downstream distance from lane taper (mile)	-0.0193	0.0071	-0.0179	0.0055
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.0900	0.0458	-0.1023	0.0382
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0687	0.0356	-0.0789	0.0297
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0705	0.0400	-0.0848	0.0339
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0690	0.0351	-0.0791	0.0297
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-----
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-----
Logarithm of 85th percentile car speed	0.2678	0.2077	0.2861	0.1608
Logarithm of truck speed deviation	0.3376	0.1464	0.3748	0.1163
RHO	0.1811	0.0905		
AR1: $N = 119$; $DW = 2.05$ [1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)				

Table **5-19**

Table **5-19**: AR1-2SLS estimates for logarithm of truck speed deviation

	$\hat{\delta}^{AR1}_{2SLS}$	S.E. $\{\hat{\delta}^{AR1}_{2SLS}\}$	$\hat{\delta}_{2SLS}$	S.E. $\{\hat{\delta}_{2SLS}\}$
Constant	3.6770	1.2394	3.6943	1.0643
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0712	0.0486	0.0772	0.0431
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-----
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-----
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	-----
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1098	0.0457	-0.1189	0.0403
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-----
Total paved width (ft)	-0.0046	0.0038	-0.0050	0.0034
Downstream distance from lane taper (mile)	-0.0141	0.0109	-0.0142	0.0095
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-----
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-----
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0448	0.0384	-0.0450	0.0340
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1879	0.0421	-0.1898	0.0362
Inverse of horizontal curve radius (1/ft x 1000)	-0.3092	0.1135	-0.3193	0.1039
Logarithm of 85th percentile truck speed	-0.5533	0.2755	-0.5541	0.2350
Logarithm of car speed deviation	0.2512	0.2687	0.2522	0.2370
RHO	0.0721	0.0918		

AR1: $N = 119$; $DW = 2.02$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Models with a lagged speed variable included exogenous variables, endogenous variables and the LHS variable lagged one time period on the RHS. The lagged variable was treated as an exogenous variable since it was predetermined (i.e. its value was determined prior to time period *t*). An example equation with a lagged speed variable is illustrated in Eq. **5.18**.

Eq. **5.18**

$$\ln s_c = \alpha_{sc} + X_{sc}\beta_{sc} + \gamma_{sc1}\ln s_t + \gamma_{sc2}\ln d_c + \lambda_{sc}\ln s_{c(t-1)} + \varepsilon_{sc} \qquad \mathbf{5.18}$$

A disadvantage of this model is inconsistent least-squares estimates if both a lagged variable and autocorrelation are present. This issue is resolved in **6.1**.

The upstream speed was the lagged speed value for first location in the lane taper of each work zone. The nearest upstream work zone speed was the lagged speed value for the remainder of the locations. The following general observations were made:

- Magnitudes and signs of parameter estimates were stable between 2SLS and 3SLS with and without the lagged speed variable.
- Standard errors were stable between 2SLS and 3SLS with and without the lagged speed variable in all equations except the logarithm of 85th percentile truck speed, where standard errors increased.
- The regression coefficient for the lagged speed variable was statistically significant in equations for logarithm of 85th percentile truck speed and passenger car speed deviation; these results agreed with the AR1-2SLS models.
- Standard errors of 3SLS estimates were 2 to 12 percent smaller than respective 2SLS estimates.
- Positive autocorrelation was still present in both 85th percentile speed equations with lagged speed variables, but the magnitude was small. Results of hypothesis tests using the Durbin-Watson test statistic were inconclusive.

Only 3SLS estimations of models with lagged speed variables (3SLS-L) are reported given the stability in parameter signs and magnitudes and efficiency gains of 3SLS over 2SLS.

Parameter estimates, standard errors, t-statistics and reduced form coefficients are provided in Table **5-20** through Table **5-23**.

Table **5-20**

Table **5-20**: 3SLS-L estimates for logarithm of 85th percentile passenger car speed

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	-0.1221	0.1576	-0.78	3.3690
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0190	0.0069	2.74	0.0374
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	-0.0748
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.1041
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	0.0676
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.1103
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	0.0334
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-0.0239
Total paved width (ft)	-----	-----	-----	0.0015
Downstream distance from lane taper (mile)	-----	-----	-----	-0.0051
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0344
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0117
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.0115
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.0086
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0194
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0148
Logarithm of 85th percentile truck speed	1.0161	0.0527	19.27	
Logarithm of car speed deviation	0.0562	0.0185	3.04	
Logarithm of 85th percentile car speed lagged one time interval	-0.0011	0.0359	-0.03	0.1519
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	0.0329
Logarithm of car speed deviation lagged one time interval	-----	-----	-----	-0.0375
Logarithm of truck speed deviation lagged one time interval	-----	-----	-----	0.0059

$N = 119$; $SSE = 0.0811$; $R^2 = 0.917$; $R^2_{adj} = 0.914$; $DW = 1.75$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-21**

Table **5-21**: 3SLS-L estimates for logarithm of 85th percentile truck speed

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	1.4420	0.3419	4.22	3.0121
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.0086
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.0328	0.0095	-3.45	-0.0755
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.0335	0.0118	2.85	0.0787
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.0385	0.0117	3.29	0.0728
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.0459	0.0147	3.13	0.0923
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.0202	0.0086	2.36	0.0397
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.0131	0.0066	-1.98	-0.0278
Total paved width (ft)	0.0009	0.0007	1.36	0.0016
Downstream distance from lane taper (mile)	-----	-----	-----	-0.0015
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0158
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0166
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.0010
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.0080
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0157
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0301
Logarithm of 85th percentile car speed	0.5526	0.1110	4.98	
Logarithm of 85th percentile car speed lagged one time interval	-----	-----	-----	0.0904
Logarithm of 85th percentile truck speed lagged one time interval	0.0811	0.0465	1.74	0.1636
Logarithm of car speed deviation lagged one time interval	-----	-----	-----	-0.0357
Logarithm of truck speed deviation lagged one time interval	-----	-----	-----	0.0242

$N = 119$; $SSE = 0.0818$; $R^2 = 0.898$; $R^2_{adj} = 0.890$; $DW = 1.65$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-22**

Table **5-22**: 3SLS-L estimates for logarithm of passenger car speed deviation

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	-0.2774	0.6409	-0.43	1.1171
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.0168
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----	-----	-----	0.0148
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.0270
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-0.0144
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.0938
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-0.0289
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.0343
Total paved width (ft)	-0.0035	0.0023	-1.54	-0.0053
Downstream distance from lane taper (mile)	-0.0136	0.0053	-2.54	-0.0206
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.1074	0.0355	-3.03	-0.1470
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.0598	0.0279	-2.14	-0.0460
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.0801	0.0315	-2.54	-0.1097
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0618	0.0279	-2.22	-0.0774
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.0264
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.0156
Logarithm of 85th percentile car speed	0.3278	0.1547	2.12	
Logarithm of truck speed deviation	0.3321	0.1118	2.97	
Logarithm of 85th percentile car speed lagged one time interval	-----	-----	-----	0.1487
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	-0.0358
Logarithm of car speed deviation lagged one time interval	0.1465	0.0696	2.11	0.2195
Logarithm of truck speed deviation lagged one time interval	-----	-----	-----	-0.0428

$N = 119$; $SSE = 1.414$; $R^2 = 0.639$; $R^2_{adj} = 0.609$; $DW = 1.96$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

Table **5-23**

Table **5-23**: 3SLS-L estimates for logarithm of truck speed deviation

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	2.7887	0.9906	2.82	0.9999
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.0753	0.0402	1.87	0.0542
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-----[1]	-----	-----	0.0554
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-0.0586
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-0.0505
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.0055
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.1220	0.0359	-3.40	-0.1366
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.0467
Total paved width (ft)	-0.0043	0.0030	-1.41	-0.0074
Downstream distance from lane taper (mile)	-0.0096	0.0080	-1.20	-0.0129
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.0391
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.0144
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.0263
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.0196	0.0301	-0.65	-0.0425
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.1541	0.0333	-4.64	-0.1284
Inverse of horizontal curve radius (1/ft x 1000)	-0.2585	0.0919	-2.81	-0.2806
Logarithm of 85th percentile truck speed	-0.4342	0.2198	-1.98	
Logarithm of car speed deviation	0.4364	0.1888	2.31	
Logarithm of 85th percentile car speed lagged one time interval	-----	-----	-----	0.3844
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	-0.2386
Logarithm of car speed deviation lagged one time interval	-----	-----	-----	0.0398
Logarithm of truck speed deviation lagged one time interval	0.0442	0.0717	0.62	0.1245

$N = 119$; $SSE = 2.060$; $R^2 = 0.609$; $R^2_{adj} = 0.573$; $DW = 1.95$

[1] preliminary testing showed structural parameter not statistically significant (*p-value* > 0.33)

5.6 Summary of Statistical Findings

This section summarizes the findings of **5.2** through **5.5**. Results of model estimations in Chapter **4** indicated possible inter-relationships between 85th percentile passenger car and truck speeds and respective speed deviations. Simultaneous equation models were estimated to test this hypothesis**.**

Estimation began with 2SLS, which is the most widely used estimator of simultaneous equation models because of its robustness in the presence of specification errors [**57**]. The 2SLS estimator is consistent, but inefficient, if there are contemporaneous correlations between disturbances of equations. As a rule-of-thumb, 3SLS is superior to 2SLS if the contemporaneous correlation between the errors of any two equations exceeds one-third [**57**]. 2SLS residuals showed correlations between equation errors were as high as 0.55. Therefore, 3SLS was used and converged to the same specification as 2SLS, but was more efficient. In some cases, the bias of OLS is accepted for a possible decrease in MSE over 2SLS and 3SLS. Therefore, OLS estimates were computed.

Residual plots and estimates of the Durbin-Watson statistic indicated positive autocorrelation. This was expected given the nature of the data collection with repeated observations in each work zone. Two techniques to address autocorrelation were identified:

- First order autoregressive model estimated with 2SLS (AR1-2SLS); and
- Specification of a lagged speed variable (by one time period) on the RHS.

Models with lagged speed variables were estimated with 2SLS and 3SLS. Only 3SLS results were reported given the stability in parameter signs and magnitudes between estimators and the efficiency gains of 3SLS over 2SLS. The AR1-2SLS model was superior at addressing the autocorrelation, but with a loss in efficiency compared to 3SLS. Inclusion of a lagged speed variable on the RHS with 3SLS estimation only partially addressed autocorrelation. Post-hoc hypothesis tests using the Durbin-Watson statistic were inconclusive.

Structural parameter estimates and standard errors for each of the models discussed are illustrated in Figure **5-5** through Figure **5-8**. The vertical axis displays the parameter values. The error bars display the standard error centered on the parameter estimate. Practical interpretation is provided in Chapter **6**. The remainder of this section summarizes general findings regarding model specifications and the relationships between speed magnitudes, deviations, work zone geometry and traffic control.

Figure **5-5**

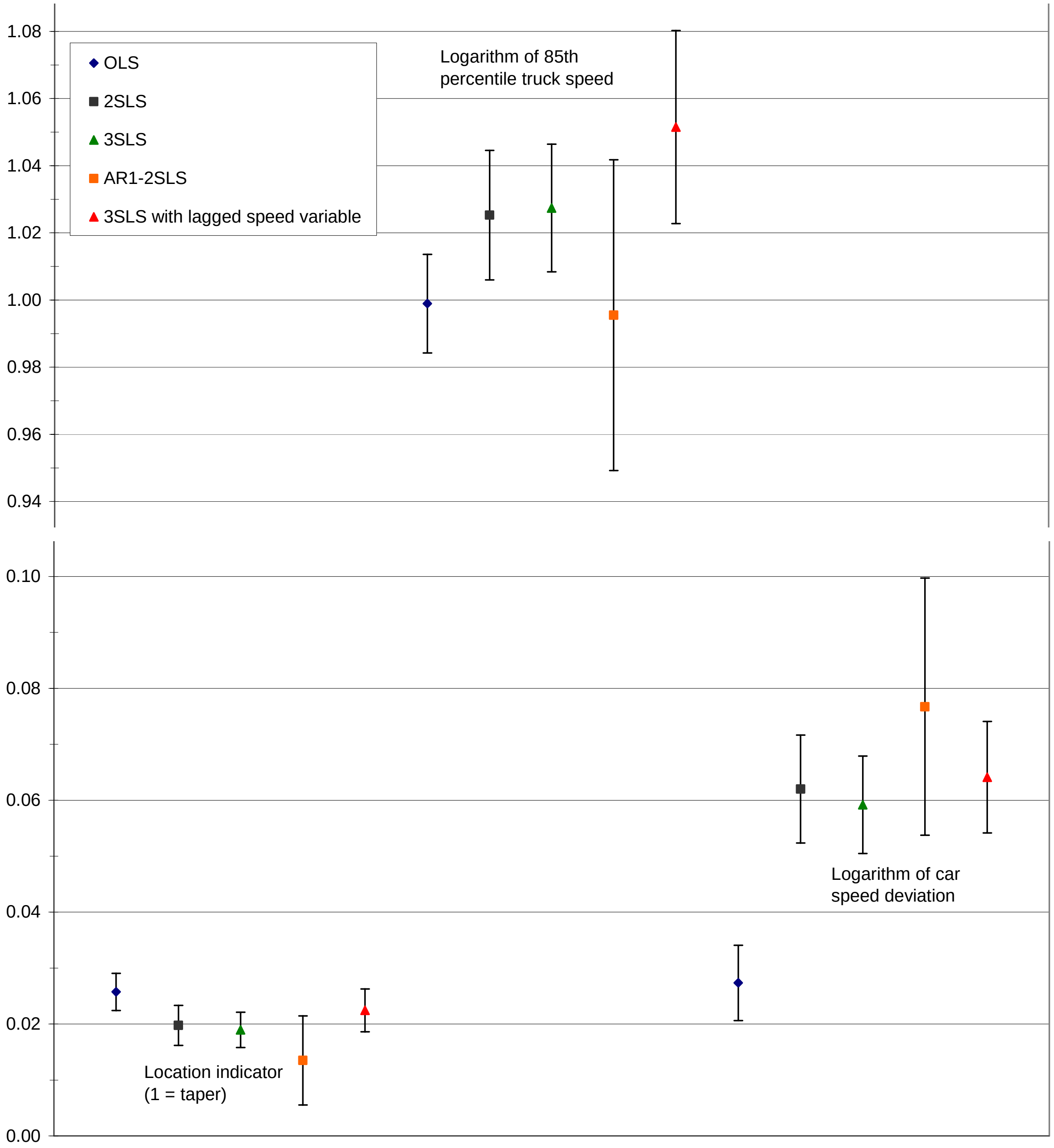

Figure **5-5**: Structural parameter estimates and standard errors for logarithm of 85th percentile passenger car speed models

Figure **5-6**

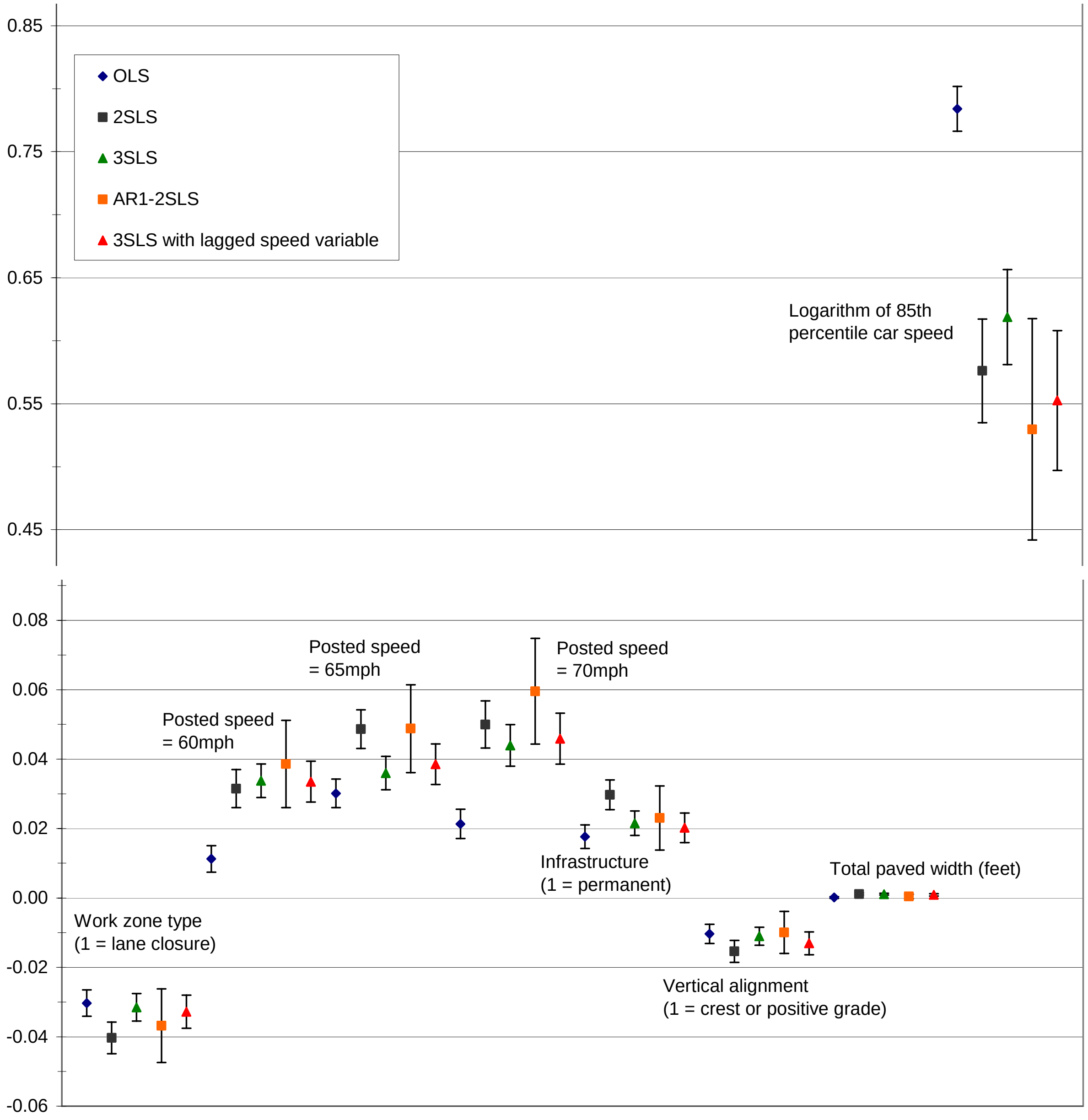

Figure **5-6**: Structural parameter estimates and standard errors for logarithm of 85th percentile truck speed models

Figure **5-7**

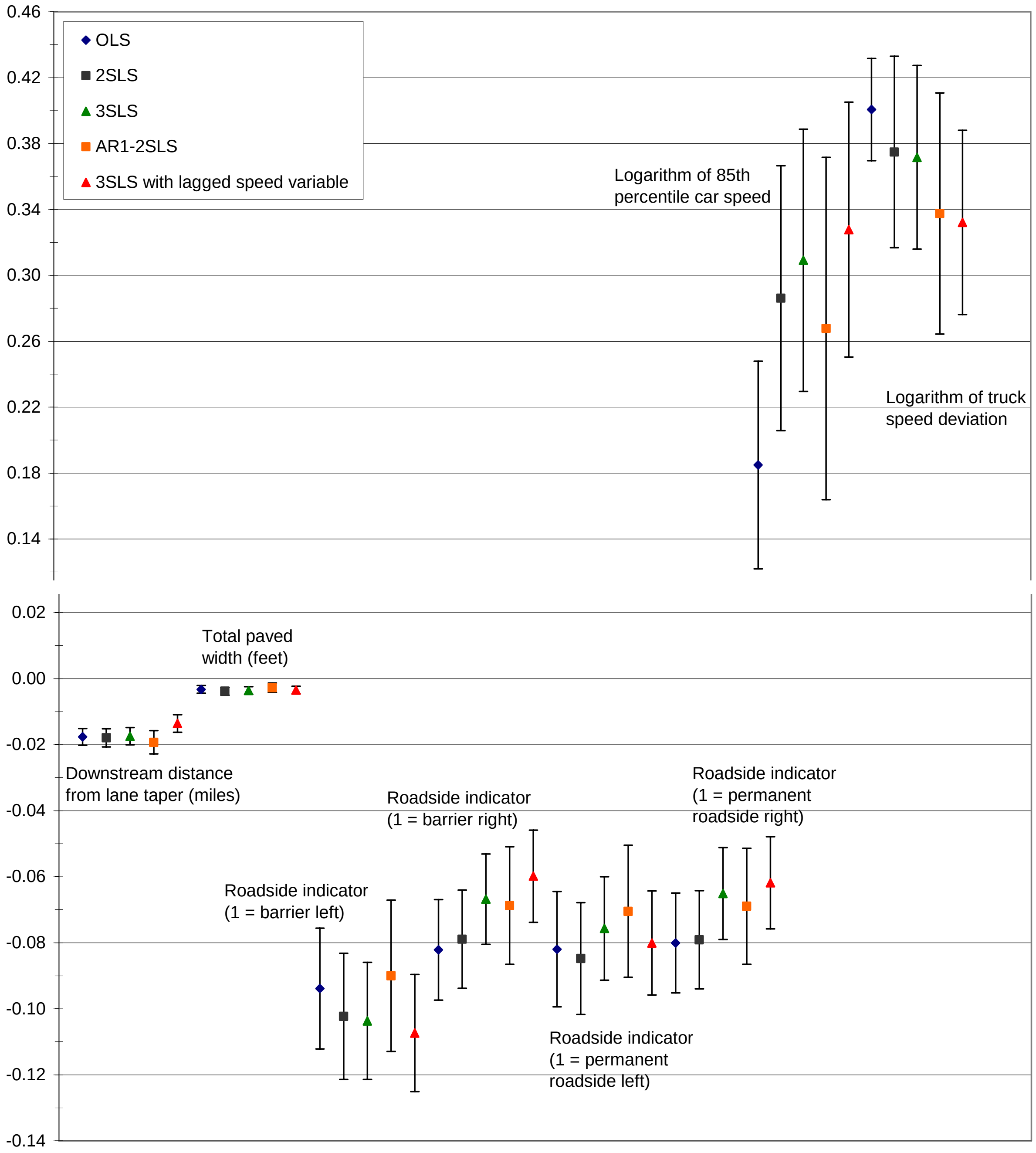

Figure **5-7**: Structural parameter estimates and standard errors for logarithm of passenger car speed deviation models

Figure **5-8**

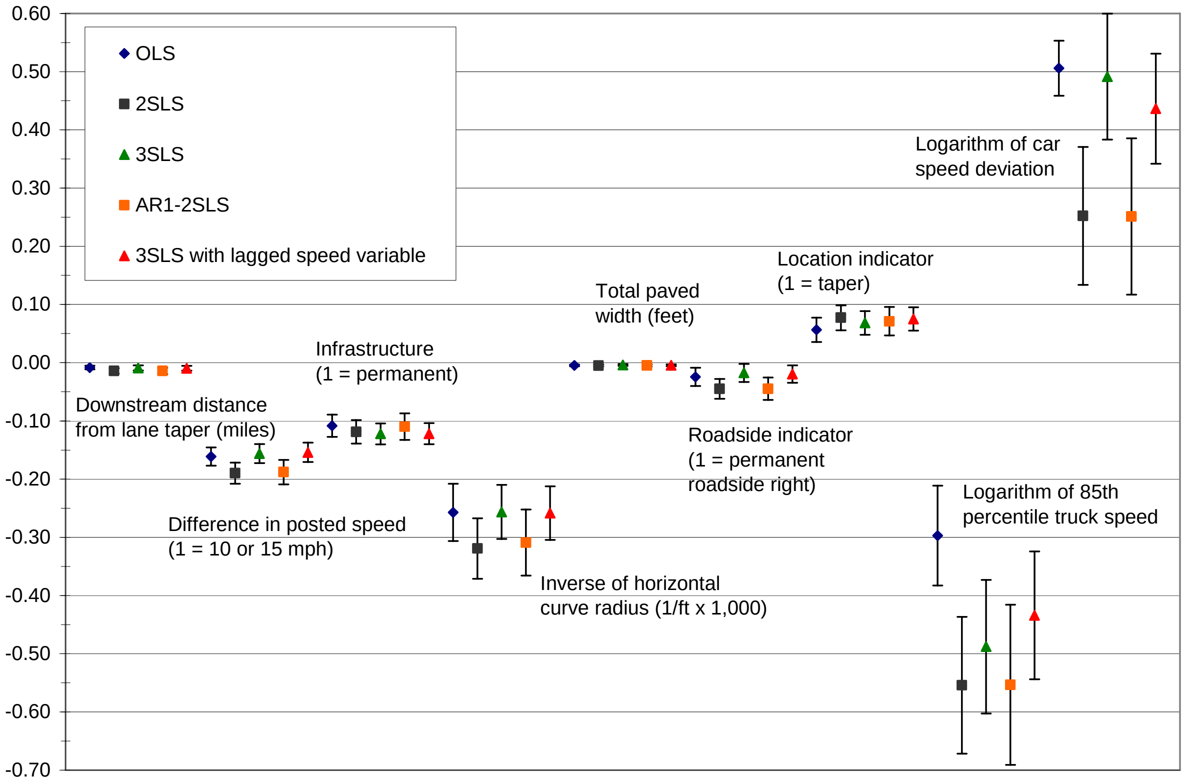

Figure **5-8**: Structural parameter estimates and standard errors for logarithm of truck speed deviation models

The simultaneous equation models appear to be a better representation of the true data generating process than the exogenous-RHS-only OLS and SUR models. Parameters for the exogenous RHS variables remained stable in sign but smaller in magnitude than parameter estimates in the Chapter **4** models. In some cases, exogenous RHS variables in Chapter **4** specifications dropped out of the respective structural equation all together. For example, results showed that work zone geometry and traffic control elements were not directly associated with 85th percentile passenger car speeds; they are indirectly associated with them through truck speeds and car speed deviations. The set of exogenous variables appearing in any of the equations in Chapter **4** remained in the system in Chapter **5**.

Some exogenous RHS variables that were statistically significant had small parameter magnitudes and may not have practical significance. Variables on the border of statistical and practical significance were kept in the simultaneous equation specifications for purposes of comparisons across estimators. These issues are addressed further in Chapter **6**.

Standard errors of the OLS estimates were smaller than for the other estimators of the simultaneous equation models. However, the OLS estimates were anywhere from approximately 93 percent smaller to 40 percent larger in magnitude than 2SLS and 3SLS estimates. It was concluded that the lower MSE of OLS was not a desirable trade-off for the simultaneous equation bias.

Contemporaneous correlations between equation disturbances were relatively large and 3SLS was more efficient than 2SLS as a result. However, the AR1-2SLS specification was superior to 3SLS with a lagged endogenous variable for addressing positive autocorrelation. In almost all cases, parameter estimates computed using AR1-2SLS versus 3SLS were similar. Further discussion and recommendations regarding this issue are provided in Chapter **6**. The following general findings regarding the structural parameters are applicable to all of the Chapter **5** models:

- The relationship between 85th percentile passenger car speed and 85th percentile truck speed was simultaneous and positive in sign (i.e. an increase in one was associated with an increase in the other).

- The relationship between 85th percentile passenger car speed and passenger car speed deviation was simultaneous and positive in sign (i.e. an increase in one was associated with an increase in the other).
- The relationship between 85th percentile truck speed and truck speed deviation was recursive and opposite in sign to that of passenger cars (i.e. an increase in one was associated with a decrease in the other).
- The relationship between passenger car speed deviation and truck speed deviation was simultaneous and positive in sign.
- 85th percentile passenger car speeds were higher in the lane taper than the remainder of the work zone. This variable was the only exogenous RHS variable in the structural equation for 85th percentile passenger car speed.
- Truck speed deviation was higher in the lane taper than the remainder of the work zone.
- 85th percentile truck speeds were slower in work zones with a lane closure strategy compared to those with a median crossover strategy.
- An increase in work zone posted speed was associated with an increase in 85th percentile truck speeds. Truck speed deviations were lowest in work zones where the posted speed was reduced by 10 or 15 mph from upstream conditions (compared to no reduction in posted speed).
- Passenger car and truck speed deviations decreased as the distance traveled in the work zone (measured by the downstream distance from the lane taper) increased. The magnitude of the speed deviation effect was similar for both cars and trucks.
- 85th percentile truck speeds were higher and truck speed deviations were lower in areas of the work zone where the temporary traveled way used permanent roadway infrastructure compared to areas where temporary infrastructure was built as part of the TTC plan.
- The presence of either a positive grade or crest vertical curve was associated with lower 85th percentile truck speeds; the magnitude of the effect was small.

- Wider total paved widths were associated with higher 85th percentile truck speeds and lower passenger car and truck speed deviations; the magnitudes of the effects were small.
- A decrease in horizontal curve radius was associated with a decrease in truck speed deviations.
- In general, passenger car speed deviations were lower in areas where there was either a temporary barrier or no traffic control device (compared to the presence of vertical panels, drums or other similar devices). The only direct effect on lower truck speed deviations was no traffic control device to the right of the traveled way; the effect was small.

Chapter 6
Recommended Work Zone Speed Model

Nine model specifications were estimated in Chapters **4** and **5**. An evaluation of the alternative model specifications and recommendation of a work zone speed model is provided in this chapter. Interpretations of structural and reduced form parameters are also included.

6.1 Evaluation of Alternative Models and Final Model Recommendation

The model structures tested were a product of the data characteristics. Three characteristics were prominent:

- Contemporaneous correlation between equation disturbances;
- Contemporaneous relationships between dependent variables; and
- Autocorrelation.

The RHS variable specifications reported were a result of comprehensive testing. Specifications in Chapters **4** and **5** were kept relatively general for parameter comparison purposes.

Trade-offs of desirable properties were apparent across models. Evaluation of the alternative structures and final model recommendation was based on four factors:

- Model characterizes data relationships;
- Parameters are consistent (see **3.7**);
- Parameters are efficient (see **3.7**); and
- Results have practical value for work zone design.

A summary of model evaluation results is provided in Table **6-1**. The complexity of the evaluation factors required a three-level qualitative assessment. For example, estimators are normally viewed as consistent or inconsistent. In the case of 3SLS-L, the estimator is consistent if inclusion of the lagged variable eliminates autocorrelation. However, if there is a lagged variable and autocorrelation of any order, the estimator is inconsistent. Reaching firm conclusions regarding n^{th} order autocorrelation is likely impossible. Simplifying assumptions are normally made.

Whether a model characterized data relationships was based on how adequately it addressed the three prominent data characteristics (listed above). None of the models fully addressed all three issues. Models that addressed at least two of the issues were labeled as partially addressing the evaluation factor (◘). Models that addressed one or less of the issues were labeled as not addressing the evaluation factor (○).

Overall, simultaneous equation models estimated with 3SLS were superior to other models and estimators; they either addressed or partially addressed all evaluation factors. The AR1-2SLS models were better than 3SLS at addressing autocorrelation but with a large loss of efficiency. A logical inquiry was whether the trade-off in efficiency was worth fully accounting for autocorrelation with the AR1-2SLS estimator or whether 3SLS or 3SLS-L was acceptable. The following observations were made:

- Inclusion of a lagged speed variable decreased first order autocorrelation coefficients.
- Durbin Watson test statistics indicated no autocorrelation in the 85th percentile passenger car speed equation with 3SLS-L (see [**59**] for details of the hypothesis test).
- Durbin Watson Test statistics for the other equations estimated with 3SLS-L yielded inconclusive results; however, values were near the upper bound of the critical Durbin Watson value for car and truck speed deviation (indicating the probability of autocorrelation is small).
- 3SLS estimates with and without lagged speed variables were very similar in magnitude indicating 3SLS-L is probably consistent (i.e. probability of autocorrelation with a lagged speed variable is small).

Table **6-1**

Table **6-1**: Evaluation of alternative models

	Exogenous RHS-Only Models				Simultaneous Equation Models				
	OLS	SUR	AR1-OLS	AR1-SUR	2SLS	3SLS	OLS	AR1-2SLS	3SLS-L[1]
Characterizes data relationships	○	○	○	○	○	◘	○	◘	◘
Parameters are consistent	●	●	●	●	●	●	○	●	◘[2]
Parameters are efficient	○[3]	●[3]	○	●	○[3]	●[3]	○[3]	○	◘[2]
Results have practical value for work zone design	●	●	●	●	●[4]	●[4]	●[4]	●[4]	●[4]

● = model adequately addresses factor
◘ = model partially addresses factor
○ = model does not address factor
[1]three-stage least squares with lagged speed variable
[2]if autocorrelation is still present after inclusion of lagged variable, then estimate is not consistent
[3]variance of estimator is likely underestimated because of positive autocorrelation
[4]through estimation of reduced form parameters

The 3SLS-L model adequately addressed positive autocorrelation and inconsistency of parameter estimates was not likely. This model is recommended over others tested. Additional observations were made regarding the 3SLS-L model presented in Table **5-20** through Table **5-23**.

- Regression coefficients for the lagged speed variable were statistically significant in equations for logarithm of 85th percentile truck speed and passenger car speed deviation; these results agreed with the AR1-2SLS models.
- Regression coefficients for total paved width were practically zero in the equations for 85th percentile truck speed and passenger car and truck speed deviation.
- Regression parameters for the downstream distance from lane taper, roadside indicator for no device in the right roadside and location indicator for lane taper in the truck speed deviation equation had relatively low t-statistics and did not contribute to the explanatory power of the model.

Estimation results for the recommended specification of the 3SLS-L model are provided in Table **6-2** through Table **6-5**. These results are used for model interpretations provided in the remainder of the document. The tables include estimated structural parameter estimates ($\hat{\delta}_{3SLS-L}$) and their standard errors (S.E. $\{\hat{\delta}_{3SLS-L}\}$), t-statistics ($t$) and reduced form parameters ($\hat{\pi}$). The following measures of model fit are also provided:

- Residual Sum of Squared Errors (SSE);
- Standard error of regression (S);
- R-squared (R^2);
- Adjusted R-squared (R_{adj}^2); and
- System R-squared (R_{system}^2).

The number of observations used for model estimation (N) is also provided.

The results of identification checks for the final specification were the same as in Table **5-6**. Correlations between endogenous variables and their respective instruments were nearly identical to those in Table **5-7**. Graphical displays of the model parameters are provided in Figure **6-1** through Figure **6-4**. The vertical axes represent the parameter values and the error bars display the standard error centered on the parameter estimate. Both structural and reduced form parameters are shown.

Table **6-2**

Table **6-2**: 3SLS estimates for logarithm of 85th percentile passenger car speed – final specification

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	-0.093	0.155	-0.60	3.389
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.022	0.006	3.55	0.043
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----[1]	-----	-----	-0.080
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.108
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	0.062
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.105
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	0.025
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	-0.023
Downstream distance from lane taper (mile)	-----	-----	-----	-0.006
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.037
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.014
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.015
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.011
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.032
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.022
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	0.192
Logarithm of car speed deviation lagged one time interval	-----	-----	-----	-0.031
Logarithm of 85th percentile truck speed	1.010	0.037	27.64	
Logarithm of car speed deviation	0.051	0.018	2.89	

$N = 119$; $SSE = 0.0806$; $S = 0.0265$ $R^2 = 0.918$; $R^2_{adj} = 0.916$; $R^2_{system} = 0.9484$

[1] structural parameter not statistically or practically significant

Table **6-3**

Table **6-3**: 3SLS estimates for logarithm of 85th percentile truck speed – final specification

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	1.291	0.274	4.72	3.052
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.015
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-0.032	0.009	-3.66	-0.080
Posted speed indicator (1 if 60 mph; 0 otherwise)	0.030	0.010	2.94	0.080
Posted speed indicator (1 if 65 mph; 0 otherwise)	0.035	0.010	3.45	0.064
Posted speed indicator (1 if 70 mph; 0 otherwise)	0.041	0.012	3.27	0.084
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.016	0.007	2.33	0.030
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-0.012	0.006	-2.05	-0.028
Downstream distance from lane taper (mile)	-----	-----	-----	-0.002
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.018
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.019
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	-0.002
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	0.011
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	-0.031
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	-0.037
Logarithm of 85th percentile truck speed lagged one time interval	0.079	0.043	1.83	0.261
Logarithm of car speed deviation lagged one time interval				-0.022
Logarithm of 85th percentile car speed	0.597	0.092	6.46	

$N = 119$; $SSE = 0.0763$; $S = 0.0263$ $R^2 = 0.906$; $R^2_{adj} = 0.899$; $R^2_{system} = 0.9484$

[1] structural parameter not statistically or practically significant

Table **6-4**: 3SLS estimates for logarithm of passenger car speed deviation – final specification

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	-0.097	0.624	-0.16	1.219
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	-0.003
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----	-----	-----	0.022
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	0.035
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	0.009
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.119
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-----	-0.001
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.032
Downstream distance from lane taper (mile)	-0.015	0.005	-2.98	-0.021
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-0.080	0.031	-2.54	-0.139
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-0.044	0.025	-1.73	-0.051
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-0.052	0.028	-1.86	-0.103
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-0.062	0.025	-2.46	-0.093
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-----	0.005
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-----	0.000
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	0.043
Logarithm of car speed deviation lagged one time interval	0.122	0.063	1.93	0.203
Logarithm of 85th percentile car speed	0.263	0.146	1.80	
Logarithm of truck speed deviation	0.357	0.118	3.02	

$N = 119$; $SSE = 1.456$; $S = 0.115$ $R^2 = 0.632$; $R^2_{adj} = 0.605$; $R^2_{system} = 0.9484$

[1] structural parameter not statistically or practically significant

Table **6-5**

Table **6-5**: 3SLS estimates for logarithm of truck speed deviation – final specification

	$\hat{\delta}_{3SLS}$	S.E. $\{\hat{\delta}_{3SLS}\}$	t	$\hat{\pi}$
Constant	2.116	0.886	2.39	1.633
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-----	0.032
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----	-----	-----	0.061
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-----	-0.051
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-----	-0.048
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	-----	0.020
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-0.074	0.028	-2.64	-0.113
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-----	0.033
Downstream distance from lane taper (mile)	-----	-----	-----	-0.015
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-----	-0.025
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	-----	0.015
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-----	0.002
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-----	-0.062
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-0.130	0.031	-4.26	-0.131
Inverse of horizontal curve radius (1/ft x 1000)	-0.193	0.084	-2.31	-0.273
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	-----	-0.031
Logarithm of car speed deviation lagged one time interval	-----	-----	-----	0.115
Logarithm of 85th percentile truck speed	-0.432	0.203	-2.13	
Logarithm of car speed deviation	0.796	0.105	7.58	
$N = 119$; $SSE = 2.394$; $S = 0.146$ $R^2 = 0.566$; $R^2_{adj} = 0.546$; $R^2_{system} = 0.9484$ [1]structural parameter not statistically or practically significant				

Figure **6-1**

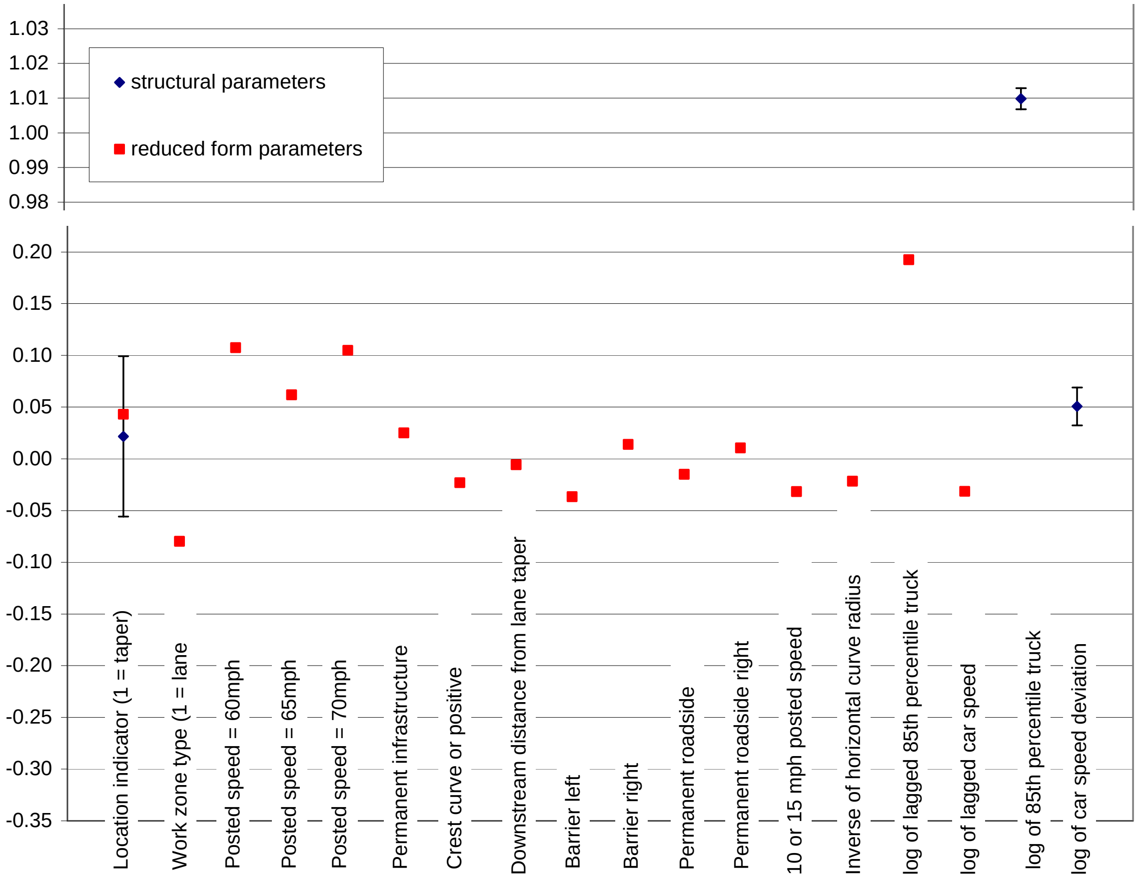

Figure **6-1**: Graphical representation of model for logarithm of 85th percentile passenger car speed - final specification

Figure **6-2**

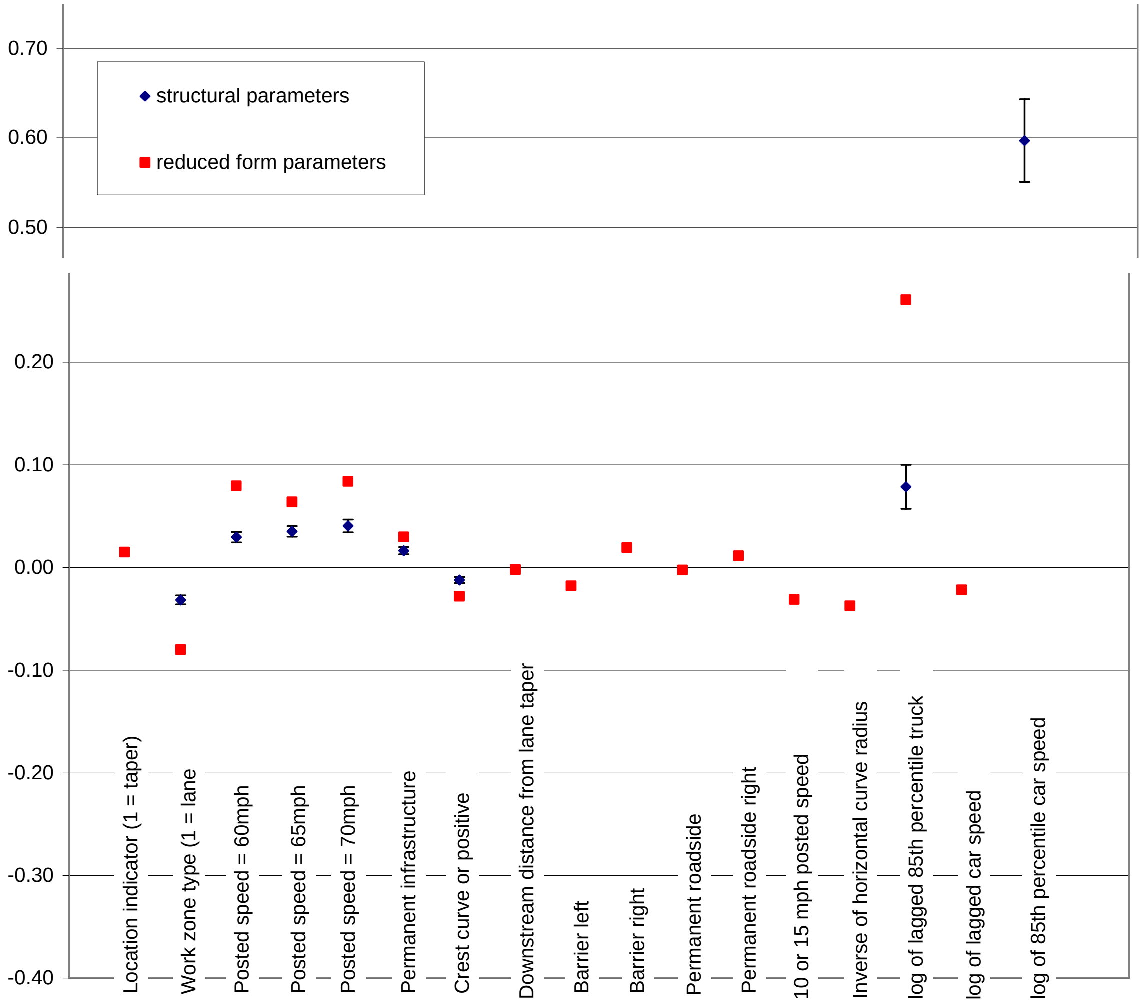

Figure **6-2**: Graphical representation of model for logarithm of 85th percentile truck speed - final specification

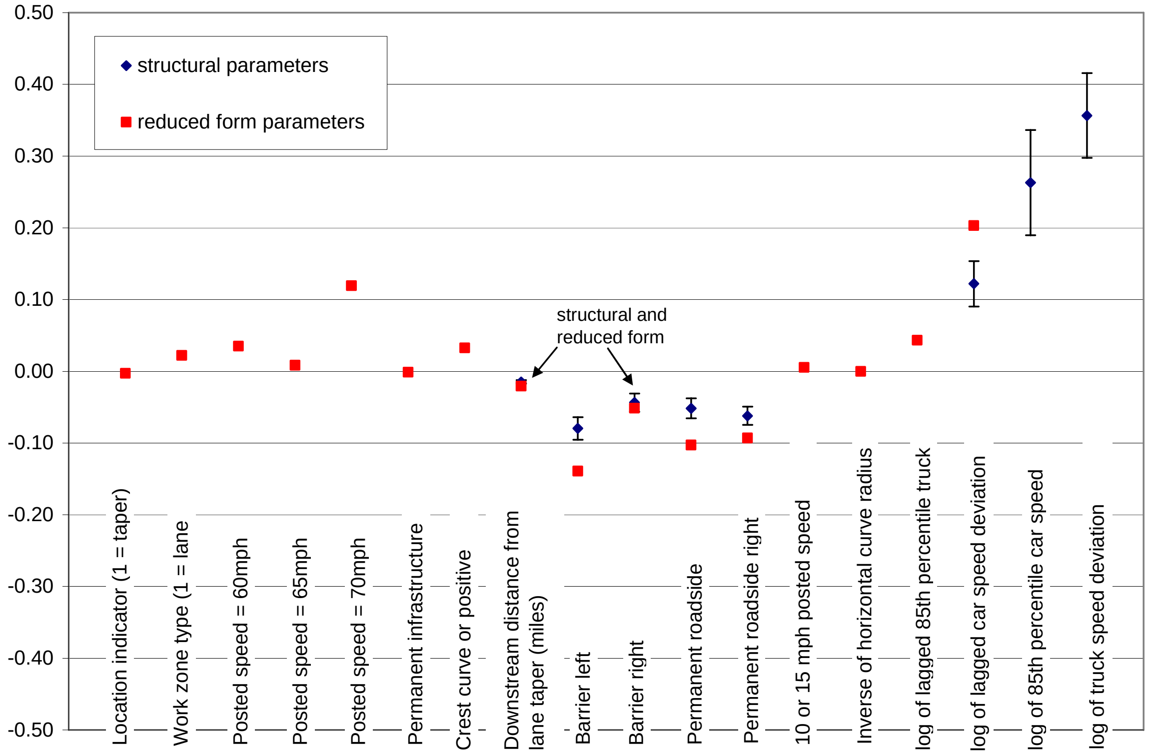

Figure **6-3**: Graphical representation of model for logarithm of car speed deviation - final specification

Figure **6-4**

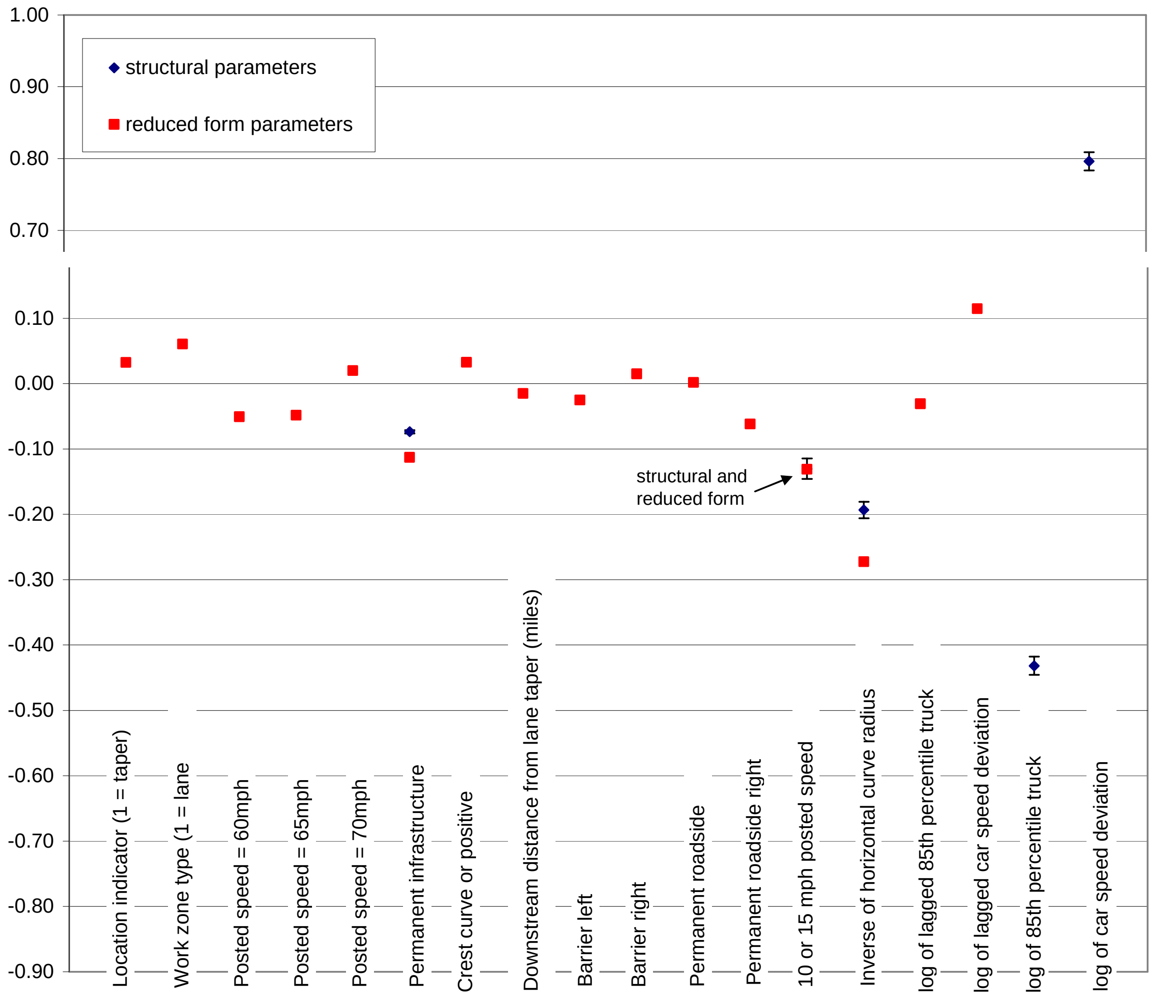

Figure **6-4**: Graphical representation of model for logarithm of truck speed deviation - final specification

6.2 Interpretation of Model Parameters

Computing marginal effects is a practical way to interpret model parameters when the LHS variable is in a logarithm form. The marginal effect is the expected percent change in the LHS variable given a one-unit change in a RHS variable. Computation of marginal effects is dependent on function form between LHS and RHS variables. Log-linear and log-log functional forms exist in the recommended speed model. Computations of marginal effects for these function forms are shown in Eq. **6.1** and Eq. **6.2**.

Eq. **6.1**

$$\text{Log-linear: } \frac{\Delta y}{Y} * 100 = \beta * 100 \qquad \textbf{6.1}$$

Eq. **6.2**

$$\text{Log-log: } \frac{\Delta y}{Y} * 100 = \frac{\beta}{X} * 100 \qquad \textbf{6.2}$$

Y and X are the LHS and RHS variables of interest. In addition to the marginal effect, the actual change in speed (in mph) resulting from a one unit change in the RHS variable can be estimated by substituting the mean of the LHS variable for Y and solving for Δy. The marginal effects and corresponding estimated changes in speed are summarized in Table **6-6** through Table **6-9**. Effects based on both structural and reduced form parameters are provided. Effects based on structural parameters represent only direct effects. They provide practical interpretations of the contemporaneous inter-relationships between 85th percentile speeds and speed deviations. The effects based on reduced form parameters represent the total effect (direct and indirect). They are important for interpretations of exogenous RHS variables and for policy or forecasting contexts. The following examples illustrate proper interpretation of the values in Table **6-6**:

- 85th percentile passenger car speeds were on average 4.3 percent (approximately 3 mph) higher in the lane taper than in the remainder of the work zone. The direct effect was 2.2 percent (1 mph).
- 85th percentile passenger car speeds increase by 1.7 percent (approximately 1 mph) for every 1 mph increase in 85th percentile truck speeds.
- 85th percentile passenger car speeds increase by 1.0 percent (approximately 0.6 mph) for every 1 mph increase in car speed deviation.
- 85th percentile passenger car speeds were approximately 8 percent (5 mph) slower in lane closures than in median crossovers.
- 85th percentile passenger car speeds decreased by 14 mph for every one unit increase in the inverse of radius of horizontal curves (in units of 1/1000 ft).

Remaining estimates of direct and indirect effects in Table **6-6** through Table **6-9** can be interpreted in the same way.

Table **6-6**

Table **6-6**: Marginal effects of explanatory variables on 85th percentile passenger car speed

	Direct Effects		Total Effects	
	Marginal effect (%)	Change in speed (mph)	Marginal effect (%)	Change in speed (mph)
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	2.2	1	4.3	3
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----[1]	-----	-8.0	-5
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	10.8	7
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	6.2	4
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	10.5	7
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	2.5	2
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	-2.3	-1
Downstream distance from lane taper (mile)	-----	-----	-0.2	0
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-3.7	-2
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	1.4	1
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-1.5	-1
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	1.1	1
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-3.2	-2
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-21.9	-14
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	0.3	0.2
Logarithm of car speed deviation lagged one time interval	-----	-----	-0.6	-0.4
Logarithm of 85th percentile truck speed	1.7	1		
Logarithm of car speed deviation	1.0	0.6		
[1]structural parameter not statistically or practically significant				

Table **6-7**: Marginal effects of explanatory variables on 85th percentile truck speed

	Direct Effects		Total Effects	
	Marginal effect (%)	Change in speed (mph)	Marginal effect (%)	Change in speed (mph)
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	1.5	1
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-3.2	-2	-8.0	-5
Posted speed indicator (1 if 60 mph; 0 otherwise)	3.0	2	8.0	5
Posted speed indicator (1 if 65 mph; 0 otherwise)	3.5	2	6.4	4
Posted speed indicator (1 if 70 mph; 0 otherwise)	4.1	2	8.4	5
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	1.6	1	3.0	2
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-1.2	-1	-2.8	-2
Downstream distance from lane taper (mile)	-----	-----	-0.1	0
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-1.8	-1
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	1.9	1
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	-0.2	0
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	1.1	1
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	-3.1	-2
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-38.0	-23
Logarithm of 85th percentile truck speed lagged one time interval	1.9	1	0.4	0
Logarithm of car speed deviation lagged one time interval	-----	-----	-0.4	0
Logarithm of 85th percentile car speed	1.0	1		

[1] structural parameter not statistically or practically significant

Table **6-8**

Table **6-8**: Marginal effects of explanatory variables on passenger car speed deviation

	Direct Effects		Total Effects	
	Marginal effect (%)	Change in deviation (mph)	Marginal effect (%)	Change in deviation (mph)
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	-0.3	-0.01
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----	-----	2.2	0.1
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	3.5	0.2
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	0.9	0.04
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	11.9	0.6
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-----	-----	-0.1	-0.01
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	3.2	0.2
Downstream distance from lane taper (mile)	-0.6	-0.03	-0.8	-0.04
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-8.0	-0.4	-13.9	-0.7
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-4.4	-0.2	-5.1	-0.3
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-5.2	-0.3	-10.3	-0.5
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-6.2	-0.3	-9.3	-0.5
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-----	-----	0.5	0.03
Inverse of horizontal curve radius (1/ft x 1000)	-----	-----	-0.2	-0.01
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	0.1	0.003
Logarithm of car speed deviation lagged one time interval	7.7	0.4	4.2	0.2
Logarithm of 85th percentile car speed	0.4	0.02		
Logarithm of truck speed deviation	8.3	0.4		

[1] structural parameter not statistically or practically significant

Table **6-9**

Table **6-9**: Marginal effects of explanatory variables on truck speed deviation

	Direct Effects		Total Effects	
	Marginal effect (%)	Change in deviation (mph)	Marginal effect (%)	Change in deviation (mph)
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	-----[1]	-----	3.2	0.1
Indicator of work zone type (1 if lane closure; 0 if median crossover)	-----	-----	6.1	0.3
Posted speed indicator (1 if 60 mph; 0 otherwise)	-----	-----	-5.1	-0.2
Posted speed indicator (1 if 65 mph; 0 otherwise)	-----	-----	-4.8	-0.2
Posted speed indicator (1 if 70 mph; 0 otherwise)	-----	-----	2.0	0.1
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	-7.4	-0.3	-11.3	-0.5
Vertical alignment indicator (1 if grade is positive or crest vertical curve; 0 otherwise)	-----	-----	3.3	0.1
Downstream distance from lane taper (mile)	-----	-----	-0.6	-0.03
Temporary concrete barrier indicator (1 if concrete barrier in left roadside; 0 otherwise)	-----	-----	-2.5	-0.1
Temporary concrete barrier indicator (1 if concrete barrier in right roadside; 0 otherwise)	-----	-----	1.5	0.1
Roadside type indicator (1 if no devices, i.e. normal roadside left; 0 otherwise)	-----	-----	0.2	0.01
Roadside type indicator (1 if no devices, i.e. normal roadside right; 0 otherwise)	-----	-----	-6.2	-0.3
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0 mph)	-13.0	-0.6	-13.1	-0.6
Inverse of horizontal curve radius (1/ft x 1000)	-196.9	-8.4	-277.6	-11.9
Logarithm of 85th percentile truck speed lagged one time interval	-----	-----	0.0	-0.002
Logarithm of car speed deviation lagged one time interval	-----	-----	2.4	0.1
Logarithm of 85th percentile truck speed	-0.7	-0.03		
Logarithm of car speed deviation	16.4	0.7		
[1]structural parameter not statistically or practically significant				

Observing elasticities is another way to interpret model parameters. Elasticity is the percent change in a LHS variable with respect to a small percent change in a RHS variable (usually one percent). Similar to computing marginal effects, computation of elasticity is dependent on functional form. The elasticity (η) computation for a log-linear functional form is shown in Eq. **6.3**.

Eq. **6.3**

$$\text{Log-linear: } \eta = \beta X \qquad \textbf{6.3}$$

Elasticities of indicator variables are not meaningful and were not computed. Elasticities for the two continuous RHS variables in each reduced form equation are shown in Table **6-10**. The following examples illustrate interpretation of the values in the table:

- A one percent increase in the downstream distance from the lane taper causes a 0.02 decrease in car speed deviation.
- A one percent increase in the inverse of horizontal curve radius (in thousands of feet) causes a 0.27 percent decrease in truck speed deviation.

All variables shown are inelastic (i.e. elasticity less than one) indicating low sensitivities of the speed measures to the continuous RHS variables in the reduced form equations.

Table **6-10**

Table **6-10**: Speed and speed deviation elasticity estimates

	85th percentile speed		Speed deviation	
Elasticity with respect to:	s_c	s_t	d_c	d_t
Downstream distance from lane taper (mile)	-0.0057	-0.0021	-0.0207	-0.0152
Inverse of horizontal curve radius (1/ft x 1000)	-0.0216	-0.0373	-0.0002	-0.2726

The simultaneous equation model provides insights of inter-relationships between speed magnitudes and deviations. The model showed the following endogenous relationships existed:

- The relationship between 85th percentile passenger car speed and 85th percentile truck speed was simultaneous and positive. An increase (or decrease) in speed for one vehicle type was associated with the same increase (or decrease) in speed of the other vehicle type.
- The relationship between 85th percentile passenger car speed and car speed deviation was simultaneous and positive. A 1 mph increase (or decrease) in 85th percentile speed was associated with a 0.02 mph increase (or decrease) in car speed deviation. A 1 mph increase (or decrease) in speed deviation was associated with a 0.6 mph increase (or decrease) in 85th percentile speed.
- The relationship between 85th percentile truck speed and truck speed deviation was recursive and negative. A 1 mph increase (or decrease) in 85th percentile truck speed was associated with a 0.03 mph decrease (or increase) in truck speed deviation.
- The relationship between car speed deviation and truck speed deviation was simultaneous and positive. A 1 mph increase (or decrease) in truck speed deviation was associated with a 0.6 mph increase (or decrease) in car speed deviation. Similarly, a 1 mph increase (or decrease) in car speed deviation was associated with a 0.7 mph increase (or decrease) in truck speed deviation.

The positive relationship between car speeds and car speed deviations was similar to findings in [**54**] related to speed and speed deviation in the same travel lane. The finding is opposite to that in [**55**] which showed a negative relationship between speed and speed deviation (similar to truck speed findings). Magnitudes of the endogenous relationships were much larger in [**54**] and [**55**] than in this study. This finding is likely attributable to the 4-second headway criterion used in the data collection (see **3.1.3**). A similar criterion was not used in [**54**] and [**55**] and the opportunity for vehicle-to-vehicle interactions was much greater in those studies.

In addition to the endogenous relationships, effects of work design and traffic control features on speed were observed. Both direct and total effects are important. Direct effects provide insight into which speed measure is directly influenced by a design or traffic control decision. Total effects are representative of the overall effect on a speed measure accounting for endogenous interactions.

Overall, the effects of design and traffic control decisions on speeds were small. The finding may be attributed to the higher-type facilities observed and current work zone design practice (i.e. to design for pre-work zone speeds). Restrictive radii, tight cross sections and steep grades - three likely speed-dampening features - were not present. Radii ranged from approximately 2,000 to 12,000 feet; total paved width from 12 to 48 feet (with an average of 19 feet) and grades from -4 to +3 percent (see Table **3-5**). The following points summarize the observed direct effects estimated by the simultaneous equation model:

- The only direct effect on 85th percentile passenger car speed was work zone location. Speeds were faster in the lane taper than the remainder of the work zone. The direct effect was small (approximately 1 mph).
- 85th percentile truck speeds were directly affected by work zone type, posted speed, type of infrastructure and presence of a positive grade or crest vertical curve. The effects are in the direction expected but small in magnitude. Truck speeds were:
    - slower in lane closures than median crossovers;
    - slower on positive grades and crest vertical curves than other vertical alignments;
    - slower on temporary infrastructure than permanent infrastructure; and
    - faster with posted speeds of 60, 65 or 70 mph than 50 or 55 mph.
- Car speed deviations were directly affected by the downstream distance from the lane taper and roadside characteristics. The effect of downstream distance from the lane taper was small. Deviations were lower in work zone areas with either a temporary

concrete barrier or permanent roadside conditions compared to areas with drums, vertical panels or other similar roadside devices.

- Truck speed deviations were directly affected by type of infrastructure, difference in upstream and work zone posted speed and horizontal curve radius. Deviations were:
    - lower on permanent infrastructure than temporary infrastructure;
    - lower with posted speed reductions of 10 or 15 mph than no posted speed reduction; and
    - decreased as radius of horizontal curve decreased.

The discussion of total effects is limited to those with a practical level of significance. The magnitudes are estimated from the reduced form model parameters. The largest effects on 85th percentile passenger car and truck speeds were attributable to work zone posted speed and work zone type. Passenger car speeds were approximately 4 to 7 mph faster and truck speeds 4 to 5 mph faster in work zones with posted speeds of 60, 65 or 70 mph than work zones with a 50 or 55 mph posted speed. Both passenger car and truck speeds were approximately 5 mph slower in lane closures than median crossovers.

Passenger car speed deviations were lower in work zone areas with either a temporary concrete barrier or permanent roadside conditions compared to areas with drums, vertical panels or other similar roadside devices. The total effects ranged from approximately 0.3 to 0.7 mph. In addition, passenger car speed deviations were 0.6 mph higher in work zones with a 70 mph posted speed limit compared to other posted speeds.

The total effects on truck speed deviations were similar in magnitude to the direct effects. Deviations were approximately 0.5 mph lower on permanent infrastructure than temporary infrastructure. Deviations were 0.6 mph lower in work zones with a posted speed reduction of 10 or 15 mph than in work zones with no posted speed reduction. Truck speed deviations also decreased as radius of horizontal curve decreased. Deviations decreased by 280 percent for every unit increase in the inverse of horizontal curve radius (with radius in units of 1,000 feet). A practical interpretation of the horizontal curve parameter is that estimated truck speed deviations were approximately 1.7 mph lower on curves with a 2,000 foot radius than on tangent sections. The place of these findings in meeting the overall research objectives are discussed in Chapter **7**.

Chapter 7

Summary, Conclusions and Recommendations

This research investigated relationships between 85th percentile speeds, speed deviations, roadway and roadside geometrics and traffic control in freeway work zones. Work zones accommodate construction and maintenance activities in addition to traffic movement. Reduced cross sections, increased curvature and other temporary design and traffic control features may be present, potentially resulting in deviations from pre- or post work zone operations. An estimated 73 billion vehicle-miles of travel were exposed to active or inactive work zones in 2001 [**2**]. Motorist exposure to work zones will increase as vehicle-miles traveled and funding for highway improvement projects increase. In response, policies have evolved from a narrow focus on standard TTC layouts to comprehensive evaluation and management of work zone safety and mobility impacts. Improving state processes and procedures using crash and operational data is part of new regulations. Design processes are an area of needed improvement.

The role of speed is prominent in current and recommended work zone design procedures. It is an input into several TTC decisions covered by the *MUTCD* and is central in overall work zone design philosophies. Although current work zone design guidance is heavily based on desirable speed outcomes, knowledge related to the actual speed outcomes of design decisions is limited. Several undesirable speed-related scenarios have resulted (see **1.4**).

Design guidance would benefit from an understanding of the effects of work zone design and traffic control features on speed. These effects were investigated through specification and estimation of a series of econometric models. Data for model estimation were collected at 119 locations in 17 Pennsylvania and Texas work zones. All work zones were lane closures or median crossovers on four-lane divided freeways. The models consisted of four equations with the following LHS variables:

- 85th percentile free-flow speed of passenger cars;
- 85th percentile free-flow speed of trucks;
- Speed deviation of passenger cars; and
- Speed deviation of trucks.

Conclusions related to model specification and estimation and the effects of work zone design and traffic control on 85th percentile speeds and speed deviations are provided in the following sections. The chapter concludes with recommendations for future work.

7.1 Model Specification and Estimation-Related Conclusions

Three important data characteristics were observed: contemporaneous correlation between equation disturbances, contemporaneous relationships between dependent variables and autocorrelation. Model specifications in Chapter **4** included only exogenous RHS variables. The exogenous-only specifications were consistent with most models of speed and highway geometrics (see [**39**] through [**53**]). The models were estimated with OLS and GLS with and without specification of first-order autocorrelation. The primary disadvantage of these models was their inability to address possible contemporaneous associations between 85th percentile speeds and speed deviations for passenger cars and trucks. Simultaneous equation models were used to investigate these relationships in Chapter **5**. Models were estimated with OLS, 2SLS and 3SLS. Autocorrelation was addressed in two alternative ways: specification of first-order autocorrelation and estimation with 2SLS or specification of a lagged speed variable and estimation with 3SLS. The latter adequately addressed positive autocorrelation with efficiency gains over 2SLS due to contemporaneous correlation of equation disturbances. It was recommended over other models and estimators tested (see **6.1**).

Simultaneous equation models were more representative of the speed data-generating process in work zones than exogenous only (i.e. OLS and SUR) specifications. The models illustrated direct effects of design and traffic control elements on speed magnitudes and deviations as well as total effects resulting from endogenous interactions. Interpretations of speed behavior were more accurate as a result. For example, exogenous only OLS and SUR models showed the same effect of a positive vertical grade on 85th percentile passenger car and truck speeds. This was counterintuitive given the differences in performance capabilities of the vehicle types. The simultaneous equation model showed a direct effect of vehicle grade for trucks only. Passenger cars were indirectly affected through slower truck speeds. If a modeler is interested in representing the actual data generating process, then simultaneous equation models are recommended when more than one operational measure is considered. If a modeler is only interested in total effects, then OLS and SUR models with only exogenous RHS variables are acceptable.

Model results indicated different endogenous relationships between speed magnitudes and deviations for passenger cars and trucks. The relationship between 85th percentile passenger car speed and car speed deviation was simultaneous and positive. An increase (or decrease) in one was associated with an increase (or decrease) in the other. The relationship between 85th percentile truck speed and truck speed deviation was recursive and negative. An increase (or decrease) in 85th percentile speed was associated with a decrease (or increase) in speed deviation. Changes in speed deviation did not influence 85th percentile speed. The structure of speed magnitude and deviation relationships by vehicle type has not been addressed by previous research. The differences in structure are not surprising given the differences in physical dimensions and performance capabilities between vehicle types and the same differences within the truck classification. Magnitudes of the endogenous relationships were much smaller than demonstrated in previous studies [**54**], [**55**]. This was likely attributable to the 4-second headway criterion used in the data collection (see **3.1.3**).

7.2 Modeled Effects of Work Zone Design and Traffic Control Features on Speed

Effects of work design and traffic control features on speed were observed but small in magnitude. The finding was attributed to the higher-type facilities observed and current work zone design practice (i.e. to design for pre-work zone speeds). Restrictive radii, tight cross sections and steep grades - three likely speed-dampening features - were not present in the work zone data collected (see Table **3-5**). Radii ranged from approximately 2,000 to 12,000 feet; total paved width from 12 to 48 feet (with an average of 19 feet) and grades from -4 to +3 percent.

The largest effects on 85th percentile passenger car and truck speeds were attributable to work zone posted speed and work zone type. Passenger car speeds were approximately 4 to 7 mph faster and truck speeds 4 to 5 mph faster in work zones with posted speeds of 60, 65 or 70 mph than work zones with a 50 or 55 mph posted speed. Two, previous studies indicated that posted speed did not influence operating speeds [**18**], [**26**]. A more recent effort showed that work zone speeds decrease when there is a reduction in posted speed, but not at the same magnitude as the posted speed reduction [**20**]. Changes in enforcement practices and work zone-specific education programs may have changed driver behavior since the two early studies.

Both passenger car and truck speeds were approximately 5 mph slower in lane closures than median crossovers. The work zone type indicator likely captured both observable and unobservable differences in work zone type. Proximity of work activity to the traveled way is one difference; activity is adjacent to the open travel lane in lane closures. Previous studies have indicated this to have a speed-dampening effect [**28**], [**34**]. Estimated 85th percentile speeds of passenger cars and trucks by work zone type and posted speed are shown in Table **7-1**. Several observations are worth noting:

- Agreement between posted speed and operating speed for this data is better than widely held opinions and judgments;
- Speeds do not increase with an increase in posted speed beyond 60 mph; and
- Posted speed had a direct effect on truck speeds only; passenger car speeds are likely to be higher when no trucks are present.

Table **7-1**

Table **7-1**: Model-estimated 85th percentile speeds by work zone type and posted speed

Work zone type	Work zone posted speed (mph)	Estimated 85th percentile passenger car speed (mph)	Estimated 85th percentile truck speed (mph)
Median crossover	50,55	61	59
	60	68	64
	65	65	63
	70	67	65
Lane closure	50,55	56	55
	60	62	59
	65	60	59
	70	62	60

Other factors influencing 85th percentile speeds included location in the work zone, vertical alignment and infrastructure type. The only direct effect on 85th percentile passenger car speed was work zone location. Speeds were faster in the lane taper than the remainder of the work zone. Vertical alignment and infrastructure type directly influenced truck speeds, which indirectly influenced passenger car speeds (see Table **6-6** and Table **6-7**).

Passenger car speed deviations were approximately 5 to 14 percent lower in work zone areas with either a temporary concrete barrier or permanent roadside conditions compared to areas with drums, vertical panels or other similar roadside devices. Permanent roadside conditions and temporary concrete barrier have consistency in both appearance and location. Drums, vertical panels and other "soft" devices are manually placed and easily moveable. Offsets from the traveled way and spacing between devices are variable. This primary difference may have attributed to the speed deviation results.

Passenger car speed deviations were higher in work zones with a 70 mph posted speed limit compared to other posted speeds. Similarly, truck speed deviations were lower in work zones with a posted speed reduction of 10 or 15 mph than in work zones with no posted speed reduction. Both of these findings contradict what is implied in the *MUTCD*, that a decrease in posted speed causes an increase in speed variance.

Truck speed deviations were lower on permanent infrastructure than temporary infrastructure and decreased as radius of horizontal curve decreased. These findings are likely attributable to more uniform speed selection at locations where physical features of the truck are influential (e.g. high center of gravity at locations of tighter horizontal curvature).

As indicated in Figure **1-1** additional activities are recommended before direct implementation of speed findings into work zone design practice. However, selected results and conclusions below may have near term value:

- Implied in the *MUTCD* is that lower speeds are associated with higher speed deviations. The work zone speed models confirmed this relationship for trucks, but showed the opposite relationship for passenger cars. In addition, design and traffic control decisions that lower speeds may also lower speed deviations for both vehicle types.
- Truck speed deviations were lower in work zones with a posted speed reduction of 10 or 15 mph than in work zones with no posted speed reduction. In addition, passenger car speed deviations were higher in work zones with a 70 mph posted speed limit compared to other posted speeds. Both of these findings contradict work zone posted speed guidance in the *MUTCD*, that a decrease in posted speed causes an increase in speed variance and that posted speed reductions should be avoided or limited to 10 mph for this reason.

- Drums, vertical panels and other “soft” devices are associated with higher speed deviations. Variable spacing and offsets to the traveled way compared to more continuous and uniform appearances of concrete barrier and permanent conditions may contribute to this finding.
- In work zones without speed restricting features (e.g. tight radii, narrow cross sections), the influence of design elements and traffic control devices is small. Agreement between posted speed and operating speed was better than widely held opinions and judgments. However, no geometric or traffic control elements showed a direct effect on 85th percentile passenger car speeds. Passenger car speeds were controlled mostly by truck speeds, which were directly influenced by posted speed, work zone type, type of infrastructure and vertical alignment. Higher passenger car speeds are expected during periods of flow with low truck volumes.

The remainder of this chapter addresses recommendations for future research.

7.3 Recommendations for Future Work

The following are recommendations for future work using data collected for this study and described in Chapter 3:

1. Conduct similar analyses using different levels of speed data aggregation at each location. The reported analysis aggregated 200 vehicle speeds per location onto one observation of speed magnitude and speed dispersion. Smaller levels of aggregation will increase sample size and possibly unmask additional endogenous and exogenous interactions between speed measures, geometry and traffic control. Different levels of aggregation may range from two samples of 100 vehicles to 200 individual vehicle speeds at each location.
2. Investigate the use of purely predictive modeling techniques. These include models with lagged endogenous and exogenous variables and Artificial Neural Networks.
3. Collect crash histories for Pennsylvania and Texas roadway segments where work zones were observed. Determine possible associations between modeled speed behavior and safety (i.e. crash frequencies and severities).

Additional recommendations are offered for future data collection and modeling activities:

1. Observation of a larger sample is recommended. Two sample size properties are number of vehicles observed at each location and number of locations. Large numbers of each are desirable; fewer vehicles at more locations than this study is recommended. Several other desirable data properties will increase modeling alternatives and improve understanding of work zone speed-related behavior:
    a. Collect speed data at all levels of vehicle headways and flows; these characteristics will likely influence vehicle-to-vehicle interactions, estimated relationships between speed magnitudes and deviations and effects of design and traffic control elements on different vehicle types.
    b. Continuously track vehicle speeds through work zones; this will increase the data usefulness to time series and other predictive modeling techniques.
    c. Collect before-during speed data at work zone locations. The data will likely be more useful in determining speed effects of work zone design and traffic control decisions than purely cross-sectional studies.
2. Collect before-during operational and crash data at a sample of work zones. Observe and model changes in operational measures and crash characteristics from pre-work zone to work zone conditions. Possible modeling techniques include two-stage estimation procedures where operational measures are modeled as a set of simultaneous equations and predicted values are used in crash frequency and severity estimations. The research will aid in determining operational performance measures appropriate for work zone design decisions.
3. Modeling results and respective conclusions in **7.1** and **7.2** are applicable to work zone strategies, facility types and dimensional ranges of geometric and traffic control features observed in this study. Future efforts should increase these observed ranges within the same work zone strategies and facility types to include narrower cross sections, tighter curvature and steeper grades. Work zones on other functional classifications and facility types should also be observed. Differences in design practices, traffic volumes and traffic mix on these facilities are likely to influence speed-related findings.

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Education

Doctor of Philosophy, Civil Engineering, The Pennsylvania State University, University Park, PA 16802

Master of Engineering, Civil Engineering, 2000, The Pennsylvania State University, University Park, PA 16802

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Selected Publications

Taylor, D.R., Muthiah, S., Kulakowski, B.T., Mahoney, K.M. and Porter, R.J. "An Artificial Neural Network Speed Profile Model for Construction Work Zones on High Speed Highways." In *Journal of Transportation Engineering, Vol. 133*, *No. 3*, March 2007.

Porter, R.J., Mahoney, K.M. and Ullman, G.L. "Development of Temporary Concrete Barrier Placement Guidance for Construction Work Zones using the Roadside Safety Analysis Program." In *Transportation Research Record 1984*, Transportation Research Board, National Research Council, Washington, DC, 2006.

Porter, R.J., Donnell, E.T., and Mahoney, K.M. "Evaluation of the Effects of Centerline Rumble Strips on Lateral Vehicle Placement and Speed." In *Transportation Research Record 1862*, Transportation Research Board, National Research Council, Washington, DC, 2004.

Mahoney, K.M., Porter, R.J., Taylor, D.R., Kulakowski, B.T. and Ullman, G.L. *Design of Construction Work Zones on High-Speed Highways*. NCHRP Web Only Document 105. National Cooperative Highway Research Program, Transportation Research Board, 2007.

Mahoney, K.M., Porter, R.J., Taylor, D.R., Kulakowski, B.T. and Ullman, G.L. *Design of Construction Work Zones on High-Speed Highways*. NCHRP Report 581. National Cooperative Highway Research Program, Transportation Research Board, 2007.

Porter, R. J., Hankey, J. M., Binder, S. C., & Dingus, T. A. *Enhanced Night Visibility Series, Volume VII: Phase II—Study 5: Evaluation of Discomfort Glare During Nighttime Driving in Clear Weather* (Report no. FHWA-HRT-04-138). Washington, DC: Federal Highway Administration, 2005.

Selected Committee Membership, Awards and Professional Service

Member, Transportation Research Board Committee on Operational Effects of Geometrics (AHB65), 2004 – present.
Leadership Fellow of the Eno Transportation Foundation, 2005
Mid-Atlantic Universities Transportation Center Student of the Year, 2005
Tau Beta Pi National Engineering Honor Society, Inducted May 1998
Chi Epsilon Civil Engineering Honor Society, Inducted December 1997